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Chiu et al.

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[54] **SPATIAL LIGHT MODULATOR HAVING SINGLE BIT-LINE DUAL-LATCH MEMORY CELLS**

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[73] Assignee: **Texas Instruments Incorporated**, Dallas, Tex.

[21] Appl. No.: **389,673**

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[51] **Int. Cl.**^{6} G09G 3/34

[52] **U.S. Cl.** **345/85**; 345/205

[58] **Field of Search** 345/84, 85, 205, 345/206, 98, 99, 100; 365/189.02, 189.07, 189.09, 189.11

[56] **References Cited**

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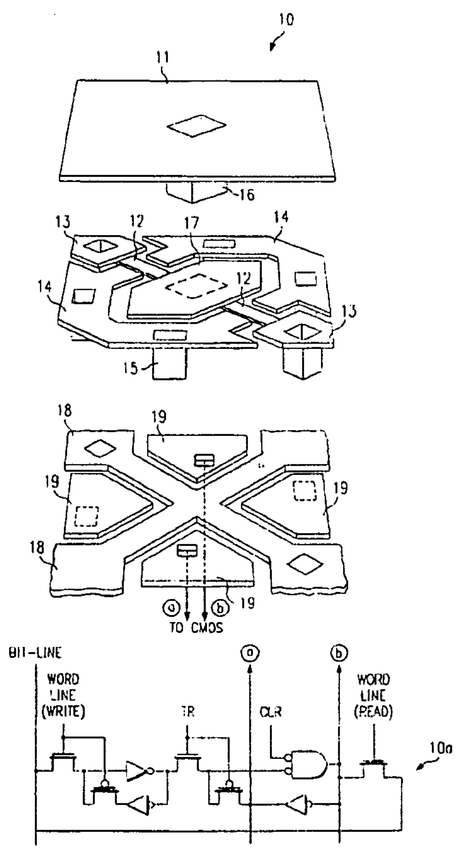
5,526,051	6/1996	Gove et al.	348/388
5,548,301	8/1996	Kornher et al.	345/85
5,583,688	12/1996	Hornbeck	359/291

Primary Examiner—Steven Saras
Attorney, Agent, or Firm—Robert C. Klinger; James C. Kesterson; Richard L. Donaldson

[57] **ABSTRACT**

A spatial light modulator (SLM) device **(30)** having a pixel array (31) and an associated memory cell array **(36)**. Each memory cell **(10*a*)** receives pixel data from a single bit-line that carries pixel data down columns of the memory cell array (36). Each memory cell **(10*a*)** has two latches **(21, 25)**. A first latch **(21)** receives data from the bit-line. A second latch (25) receives data transferred from the first latch **(21)** in response to a transfer signal, and is in electrical communication with at least one address electrode **(14)** of each pixel **(10)** of the pixel array **(31)**.

19 Claims, 2 Drawing Sheets



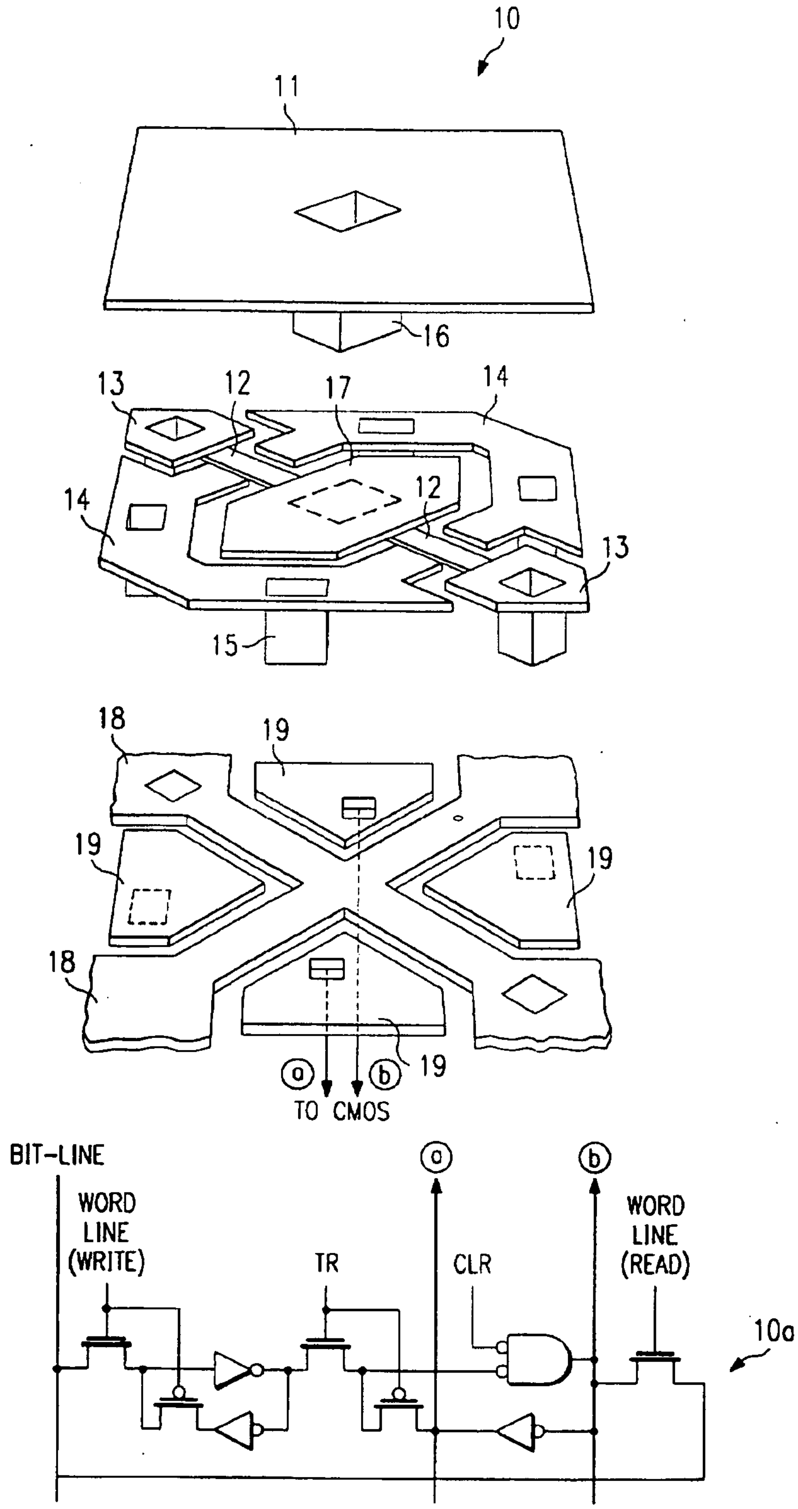

10
11
16
13
12
17
14
14
12
13
15
18
19
19
19
18
19
a
b
TO CMOS
BIT-LINE
a
b
WORD
LINE
(WRITE)
TR
CLR
WORD
LINE
(READ)
10a

FIG. 1

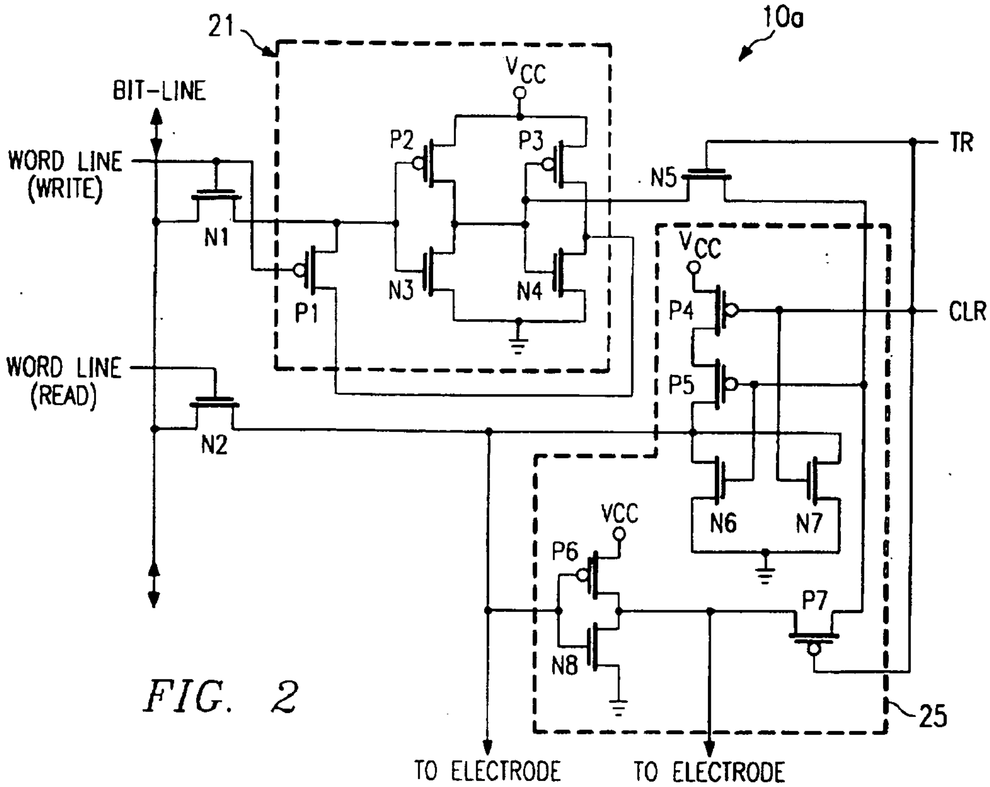

21
10a
BIT-LINE
WORD LINE
(WRITE)
VCC
P2
P3
N5
TR
N1
P1
N3
N4
VCC
P4
CLR
WORD LINE
(READ)
P5
N2
N6
N7
VCC
P6
P7
N8
25
TO ELECTRODE
TO ELECTRODE

FIG. 2

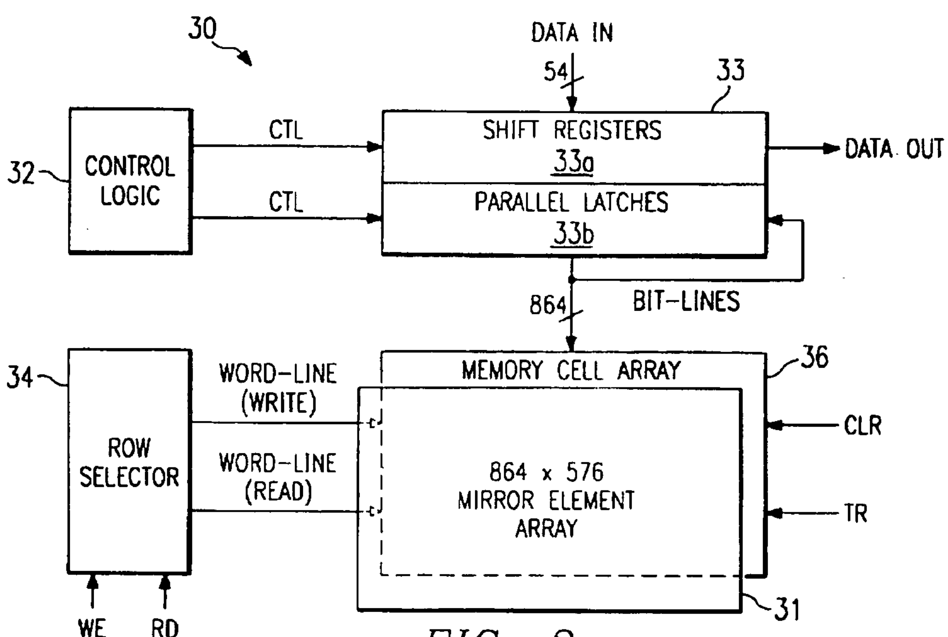

30
DATA IN
54
33
CONTROL
LOGIC
32
CTL
CTL
SHIFT REGISTERS
33a
PARALLEL LATCHES
33b
DATA OUT
864
BIT-LINES
34
ROW
SELECTOR
WORD-LINE
(WRITE)
WORD-LINE
(READ)
MEMORY CELL ARRAY
36
864 x 576
MIRROR ELEMENT
ARRAY
CLR
TR
31
WE
RD

FIG. 3

SPATIAL LIGHT MODULATOR HAVING SINGLE BIT-LINE DUAL-LATCH MEMORY CELLS

CROSS-REFERENCE TO RELATED APPLICATIONS

Cross-reference is made to the following co-pending patent applications, the teachings of which are incorporated herein by reference.

U.S. patent application Ser. No. 08/373,692 filed Jan. 17, 1995 entitled "Monolithic Programmable Format Pixel Array"

U.S. patent application Ser. No. 08/389,674, filed Feb. 16, 1995 entitled "Memory Cell Array for Digital Spatial Light Modulator".

TECHNICAL FIELD OF THE INVENTION

This invention relates to spatial light modulators, and more particularly to a spatial light modulator having a memory cell for storing data for addressing the spatial light modulator.

BACKGROUND OF THE INVENTION

Spatial light modulators (SLMs), as used for imaging applications, are arrays of pixel-generating elements that emit or reflect light to an image plane. The pixel-generating elements are often themselves referred to as "pixels", as distinguished from the pixels of the image. This terminology is clear from context so long as it is understood that more than one pixel of the SLM array can be used to generate a pixel of the image.

The pixels of the SLM are individually addressable, such that the image is defined by which pixels are on or off at a given time. Moving images can be generated by re-addressing image frames. Greyscale images can be created with various modulation schemes, and color images can be created by filtering the emitted or reflected light.

A digital micro-mirror device (DMD), sometimes referred to as a deformable micro-mirror device, is a type of SLM. It may be used to form images, and has been used in both display and printing applications. A DMD used for imaging applications such as display or printing, has an array of hundreds or thousands of tiny tilting mirrors. Light incident on the DMD is selectively reflected or not reflected from each mirror to an image plane. Each mirror is attached to one or more hinges mounted on support posts, and spaced by means of an air gap over underlying control circuitry. The control circuitry includes a memory cell associated with each mirror. Each memory cell stores a 1-bit data value, which determines the state of an applied electrostatic force applied to the mirror. This electrostatic force is what causes each mirror to selectively tilt. DMDs DMDs may be manufactured using integrated circuit techniques, with the mirror elements fabricated over a substrate that contains the memory cells. Like other integrated circuits, it is desirable to improve manufacturing output by simplifying the circuit design.

SLMs other than DMDs, as well as other types of micro-mechanical devices, might also use memory cell arrays. Regardless of the application, simplified circuit design is advantageous.

SUMMARY

One aspect of the invention is a spatial light modulator (SLM) having an array of pixels that are electrically addressable with data signals from an array of memory cells. Each memory cell is in electrical communication with at least one of the pixels via at least one address electrode. Each memory cell has a first latch that transfers pixel data to a second latch in response to a transfer signal. The second latch provides a data signal representative of the pixel data stored in that latch to the pixel. A bit-line is associated with each column of the memory cell array. Each bit-line delivers the pixel data down the bit-line to the first latch of at least one memory cell in that column. A write word-line is associated with each row of the memory cell array. Each word-line delivers a write signal for enabling a row of memory cells to be written by the data signal.

An advantage of the invention is that the memory cell array needs only one bit-line per memory cell rather than two. The simplified design improves device yield during manufacture. The use of a single bit-line reduces the circuitry required to be placed under the pixels, which permits them to be more closely spaced.

Another advantage of the invention is that the dual-latch design hastens loading of data to the SLM. When the pixel data is latched into the second latch, the first latch is freed to be loaded with new pixel data. This dual latch design is also referred to as a "shadow latch" design. The invention provides sufficiently fast data transfer rates and high fanout capability so that memory multiplexed designs can be implemented.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded view of a hidden-hinge type mirror element used in a digital micro-mirror device (DMD), and having a memory cell in accordance with the invention.

FIG. 2 is a transistor-level diagram of the memory cell of FIG. 1.

FIG. 3 is a block diagram of a DMD device having an array of mirror elements and associated memory elements in accordance with the invention and also having peripheral control circuitry.

DETAILED DESCRIPTION OF THE INVENTION

The following description is in terms of a DMD-type spatial light modulator (SLM), which has a memory cell associated with each mirror element of an array of mirror elements. The memory cells are loaded with 1-bit data values on a row-by-row basis, via bit-lines that deliver the data down columns of the memory cell array. The data loaded to each memory cell represents an address signal for tilting an associated mirror element. The invention is directed to an improved memory cell array, which requires only one bit-line per memory cell. Also, the two-latch design of the memory cells permits data to be written into one latch of a memory cell while data in the other latch is being used to address the mirror elements.

However, the invention is not limited to use with DMDs, and applies to memory cell arrays for other applications. For example, SLMs other than DMDs might be addressed with data from a memory cell array. In the case of a DMD, each pixel of the image is generated with one or more "mirror elements". In the case of an SLM, a more general term would be "pixels", which for purposes of this description refers to the elements of the SLM that generate the pixels of the image. In other words, the SLM is assumed to have individually addressable pixels that either emit or reflect light for generating pixels of an image.

FIG. 1 is an exploded perspective view of a single mirror element **10** of a DMD. For purposes of example, mirror element **10** is a hidden-hinge type mirror element. As with other DMD designs, the hinges **12** are supported on support posts **13**. Additionally, address electrodes **14** are supported by electrode posts **15** on the same level as hinges **12** and hinge support posts **13**. The mirrors **11** are fabricated above the hinge/electrode layer and are supported by mirror support posts **16**.

Mirror support post **16** is fabricated over a landing yoke **17**. Landing yoke **17** is attached to one end of each of the two hinges **12**, which are torsion hinges. The other end of each hinge **12** is attached to a hinge support post **13**. The hinge support posts **13** and electrode posts **15** support the hinges **12**, address electrodes **14**, and landing yoke **17** over a control bus **18** and address pads **19**. When mirror **11** is tilted, the tip of the landing yoke **17** contacts the control bus **18**. The control bus **18** and landing pads **19** have appropriate electrical contacts to a substrate of address circuitry, which is typically fabricated within the substrate using CMOS fabrication techniques.

The address circuit of each mirror element **10** includes a memory cell **10a**, manufactured with CMOS techniques. As explained below, each memory cell **10a** is loaded with 1 bit of data passed down a bit-line. Rows of memory cells **10a** are enabled with word-lines, which may carry either a write enable or a read enable signal. Writing is used for loading data to memory cells **10a**, whereas reading is used during testing in lieu of actual mirror operation.

In the example of this description, there is a one-to-one correspondence between memory cells **10a** and mirror elements **10**. Thus, memory cell **10a** is connected to a single pair of address electrodes **14**, via nodes a and b, for a single mirror element **10**. However, in other embodiments, groups of mirror elements **10** might share a memory cell **10a**. The memory cell **10a** would be connected to multiple pairs of address electrodes **14**, but only the mirror element **10** that is to be addressed with the stored data would be enabled. These shared memory cells are part of a "memory multiplexed" loading method described in U.S. Pat. No. 5,548,301, filed Sep. 2, 1994, entitled "Pixel Control Circuitry for Spatial Light Modulator", assigned to Texas Instruments Incorporated and incorporated by reference herein. The present invention is useful for multiplexed memory cells as well as non-multiplexed memory cells.

Another type of mirror element is the torsion beam type, whose hinges are not hidden but rather extend from opposing sides of the mirror. Still other types of DMDs are cantilever beam types and flexure beam types. The invention could, be used with a memory cell array that addresses any of these types of mirror elements. Various DMD types are described in U.S. Pat. No. 4,662,746, entitled "Spatial Light Modulator and Method"; U.S. Pat. No. 4,956,619, entitled "Spatial Light Modulator"; U.S. Pat. No. 5,061,049 entitled "Spatial Light Modulator and Method"; U.S. Pat. No. 5,083,857 entitled "Multi-level Deformable Mirror Device"; and U.S. Pat. No. 5,583,688, entitled "Multi-Level Digital Micromirror Device". Each of these patents is assigned to Texas Instruments Incorporated and each is incorporated herein by reference.

In operation for imaging applications, a light source illuminates the surface of the DMD. A lens system may be used to shape the light to approximately the size of the array of mirror elements **10** and to direct this light toward them. The mirror support post **16** permits mirror **11** to rotate under control of a hinge **12**. Mirror **11** tilts in response to an electrostatic force caused by application of an appropriate voltage to an address electrode **14**.

Voltages based on data in the memory cells **10a** of the underlying CMOS circuit are applied to the two address electrodes **14**, which are located under opposing corners of mirror 11. Electrostatic forces between the mirrors **11** and their address electrodes **14** are produced by selective application of voltages to the address electrodes **14**. The electrostatic force causes each mirror **11** to tilt either about +10 degrees (on) or about −10 degrees (off), thereby modulating the light incident on the surface of the DMD. Light reflected from the "on" mirrors **11** is directed to an image plane, via display optics. Light from the "off" mirrors **11** is reflected away from the image plane. The resulting pattern forms an image. Various modulation techniques can be used to form greyscale images, and color images can be created with filtered light.

In effect, the mirror **11** and its address electrodes **14** form capacitors. When appropriate voltages are applied to mirror **11** and its address electrodes **14**, a resulting electrostatic force (attracting or repelling) causes the mirror **11** to tilt toward the attracting address electrode **14** or away from the repelling address electrode **14**.

Once the electrostatic force between the address electrodes 14 and the mirror **11** is removed, the energy stored in the hinge 12 provides a restoring force to return the mirror 11 to an undeflected position. Appropriate voltages may be applied to the mirror **11** or address electrodes **14** to aid in returning the mirror **11** to its undeflected position.

Further details describing the use of DMDs for display applications may be found in U.S. Pat. No. 5,079,544, entitled "Standard Independent Digitized Video System"; in U.S. Pat. No. 5,526,051, entitled "Digital Television System"; and in U.S. Pat. No. 5,452,024, entitled "DMD Display System."Each of these patents and patent applications is assigned to Texas Instruments Incorporated, and each is incorporated herein by reference.

FIG. 2 is a transistor-level circuit diagram of the memory cell **10a** of FIG. 1. As in FIG. 1, each memory cell **10a** has only one bit-line, which is bi-directional.

Memory cell 10a is essentially comprised of two latches, a primary latch **21** and a secondary latch **25**. Primary latch **21** is comprised of transistors **P1**, **P2**, **P3**, **N3**, and **N4**. Secondary latch 25 is comprised of transistors **P4**, **P5**, **P6**, **P7**, N6, N7, and N8. The prefixes "N" and "P" identify the respective transistors as NMOS or PMOS transistors, respectively.

For write operation, the write word line is high and the read word line is low. Pixel data on the bit-line is written into a first latch **21** via a write switch, **N1**. The read word line is low, so that N2 is off. When a high transfer (TR) pulse is applied, N5 is on and **P7** is off. This causes the data stored in the primary latch **21** to be transferred to the secondary latch **25** via an output line connected to the node between **P2** and N3. When the data transfer is complete, **N5** is turned off and P7 is turned on. The true and complement outputs of the secondary latch **25** drive the address electrodes of the associated mirror element **10** when transistor **P7** is on. By having transistor P7 off when transferring data between latches, the transfer speed is fast because the secondary latch 25 need not instantaneously drive the address electrodes.

For read operation, the read word-line is high and the write word-line is low. The read switch N2 is on. This causes data latched in the second latch **25** to be read out via N2 to the bit-line. The bit-line is this bi-directional.

For clear operation, the clear (CLR) line is high, which sets the data in the second latch **25** to zero. The clear

function is used to clear all memory cells 10*a* of the display to a black state in a short time period. If there were no clear feature, the AND gate of FIG. 1 (transistors P4, P5, N6, and N7 of FIG. 2) for the CLR input would be replaced with an inverter.

FIG. 3 is a block diagram of a DMD device 30 having a mirror element array 31 fabricated over a memory cell array 36. The mirror element array 31 has mirror elements 10, and the memory cell array 36 has memory cells 10*a*, such as those of FIG. 1.

DMD device 30 also has peripheral a control circuitry, including a control logic circuit 32, a pixel data loading circuit 33, and a row selector 34. As explained above, in the example of this description, there is a one-to-one correspondence between memory cells 10*a* and mirror elements 10, such that each memory cell 10*a* of array 36 is connected to the address electrodes of a single mirror element 10, as in FIG. 1. In the example of this description, array 31 has 864 mirror elements per row (864 columns) and 576 rows of mirror elements. This is a typical array size for display applications.

Each memory cell of array 36 receives the input signals described above in connection with FIG. 2. As is also illustrated in FIG. 3, these input signals include a pixel data signal on its bit-line, a read or a write signal on the word-lines, a data transfer signal (TR), and optionally a clear signal (CLR).

Data is loaded into array 36 via data loading circuit 33 in a special "bit-plane" format. Instead of being in pixel format, where data is ordered by pixel, row, frame, the data is ordered by bit, row, bit-plane, frame. In other words, the primary order of the data is bit-by-bit, with all bits of one bit weight for all pixels being ordered together, then all bits of another bit weight, etc. For example, 8-bit pixel data would be ordered into 8 bit-planes, each bit-plane being comprised of the data for 1 bit of 8 bit weights. This permits all mirror elements 10 of DMD device 30 to be simultaneously addressed with an electrical signal corresponding to a 1-bit value loaded to their associated memory cells 10*a*. The length of time that any one mirror element 10 remains on is controlled in accordance with the bit weight.

The formatting of data in this manner permits a type of pulse width modulation, which permits DMD device 30 to generate greyscale images. For display applications, further details describing pulse width modulation and the formatting of data for input to DMD device 30 are set out in U.S. Pat. No. 5,278,652, entitled "DMD Architecture and Timing for Use in a Pulse Width Modulated Display System", assigned to Texas Instruments Incorporated and incorporated by reference herein.

Although all mirror elements 10*a* of array 31 are simultaneously addressed, the memory cells 10*a* of array 36 are loaded on a row-by-row basis. This is accomplished with data loading circuit 33. It is only after all memory cells 10*a* of array 36 are loaded that the mirror elements 10 of array 31 are addressed via their address electrodes 14. Control logic circuit 32 provides timing and control signals that synchronize the data loading circuit 33 and row selector 24 to the data being loaded.

Data loading circuit 33 is comprised of a number of shift registers 33*a*. During one clock period, each shift register 33*a* receives 1 bit of data. Thus, for n-bit shift registers 33*a*, the load cycle to fill shift registers 33*a* requires n clock periods. For example, for an 864-column array, 54 16-bit shift registers 33*a* each receive a 1-bit value during each clock cycle, with 16 clock cycles for loading one row of data.

After shift registers 33*a* receive one row of data, they pass this row data in parallel to parallel latches 33*b*. Parallel latches 33*b* hold the row data, while shift registers 33*a* are receiving the next row.

Parallel latches 33*b* provide the row data in parallel on the bit-lines to a row of memory cell array 36. More specifically, they hold the row data on the bit-lines, such that each column of memory cells 10*a* receives a data signal representing a bit of data. The row of memory cells of array 36 that is to receive the row data is selected with row selector 34. The row selector 34 provides a row address, which it may generate with a counter for loading consecutive rows, and includes a decoder.

Control logic circuit 32 provides timing and control signals that synchronize the data loading circuit 33 and the row selector 34. Further details of the loading circuit 33 are set out in U.S. patent Ser. No. 08/373,692, entitled "Monolithic Programmable Format Pixel Array", assigned to Texas Instruments Incorporated and Incorporated by reference herein.

Other Embodiments

Although the invention has been described with reference to specific embodiments, this description is not meant to be construed in a limiting sense. Various modifications of the disclosed embodiments, as well as alternative embodiments, will be apparent to persons skilled in the art. It is, therefore, contemplated that the appended claims will cover all modifications that fall within the true scope of the invention.

What is claimed is:

1. A spatial light modulator, comprising:

an array of electrically addressable pixels, arranged in rows and columns;

a memory cell array, arranged in rows and columns, each memory cell being in data communication with at least one of said pixels, each said memory cell having a first latch in data communication with a second latch, said first latch transferring pixel data to said second latch in response to a transfer signal, said second latch providing an address signal representative of said pixel data to said at least one of said pixels with which said memory cell is in data communication;

a bit-line associated with each said column of said memory cell array, each said bit-line delivering said pixel data to the first latch of each said memory cell in its associated column of said memory cell array; and

a write word-line associated with each said row of said memory cell array, each said word-line delivering a write signal enabling its associated row of said memory cell array to be written with said pixel data.

2. The spatial light modulator of claim 1, wherein each said memory cell further has a write switch at an input to said first latch, said write switch being enabled by said write word-line and said write switch controlling whether said pixel data on said bit-line is delivered to said memory cell.

3. The spatial light modulator of claim 1, wherein each said bit-line is bi-directional, further comprising a read word-line associated with each said row of said memory cell array, each said read word-line delivering a read signal enabling said row of said memory cell array to deliver said pixel data to said bit-lines.

4. The spatial light modulator of claim 3, wherein each said memory cell further has a read switch at an output of said memory cell, said read switch being enabled by said read signal and said read switch controlling whether said pixel data is delivered to said bit-line.

5. The spatial light modulator of claim 4, wherein said read switch is connected to an output of said second latch.

6. The spatial light modulator of claim 1, wherein each said memory cell is in electrical communication with a single one of said pixels.

7. The spatial light modulator of claim 1, wherein each said pixel has a true address electrode and a complement address electrode, and wherein each said second latch has a true output and a complement output connected to said true address electrode and said complement address electrode, respectively.

8. The spatial light modulator of claim 7, wherein each said memory cell is in electrical communication with multiple of said pixels.

9. The spatial light modulator of claim 8, wherein said pixels each comprise a deflectable mirror positioned over said address electrodes.

10. The spatial light modulator of claim 1, wherein each said second latch has a switch responsive to a clear signal for loading data directly to said second latch.

11. A digital micro-mirror device comprising: an array of mirror elements, each mirror element being electrically addressable in response to an address signal applied at an address electrode;

a memory cell array, arranged in rows and columns, for storing pixel data representing the state of said address signal, each memory cell being in data communication with at least one of said mirror elements, wherein each said memory cell has a first latch and a second latch in data communication with said first latch, said first latch transferring said pixel data to said second latch in response to a transfer signal, said second latch providing said address signal to at least one said pixel;

a single bit-line associated with each said column of said memory cell array, each said bit-line delivering pixel data to its associated column of said memory cell array; and

a write word-line associated with each said row of said memory cell array, each said word-line delivering a write signal enabling its associated row of said memory cell array to be written with said pixel data.

12. The device of claim 11, wherein each said mirror element has a true address electrode and a complement address electrode, and wherein each said second latch has a true output and a complement output connected to said true address electrode and said complement address electrode, respectively.

13. The device of claim 12, wherein said mirror elements each comprise a deflectable mirror positioned over said address electrodes.

14. The device of claim 11, further comprising a data loading circuit receiving said pixel data on a row-by-row basis and delivering said pixel data to said memory cell array via said bit-lines.

15. The device of claim 14, further comprising a row selector for determining which said row of said memory cell array is to receive said row of data.

16. The device of claim 11, further comprising a read word-line associated with each said row of said memory cell array, each said read word-line delivering a read signal enabling said row of said memory cell array to deliver said pixel data to said bit-lines.

17. The device of claim 11, wherein each said memory cell is in electrical communication with a single one of said mirror elements.

18. The device of claim 11, wherein each said memory cell is in electrical communication with multiple of said mirror elements.

19. The device of claim 11, wherein each said memory cell has a first latch and a second latch in data communication with said first latch, said second latch providing said address signal, said first latch transferring said pixel data to said second latch in response to a transfer signal.

* * * * *

US006128122A

United States Patent [19]

Drake et al.

[11] Patent Number: 6,128,122

[45] Date of Patent: Oct. 3, 2000

[54] **MICROMACHINED MIRROR WITH STRETCHABLE RESTORING FORCE MEMBER**

[75] Inventors: **Joseph D. Drake**; **John H. Jerman**, both of Palo Alto; **John D. Grade**, Mountain View, all of Calif.

[73] Assignee: **Seagate Technology, Inc.**, Scotts Valley, Calif.

[21] Appl. No.: **09/398,259**

[22] Filed: **Sep. 17, 1999**

Related U.S. Application Data

[63] Continuation-in-part of application No. 09/231,317, Jan. 13, 1999, Pat. No. 5,999,303, and a division of application No. 08/823,422, Mar. 24, 1997, abandoned.

[60] Provisional application No. 60/100,989, Sep. 18, 1998.

[51] **Int. Cl.**[7] **G02B 26/08**

[52] **U.S. Cl.** **359/224**; 359/198; 359/199; 359/223; 359/224; 369/112; 369/44.14

[58] **Field of Search** 359/198, 199, 359/212–214, 223, 224, 848, 871; 369/44.11, 44.14, 112

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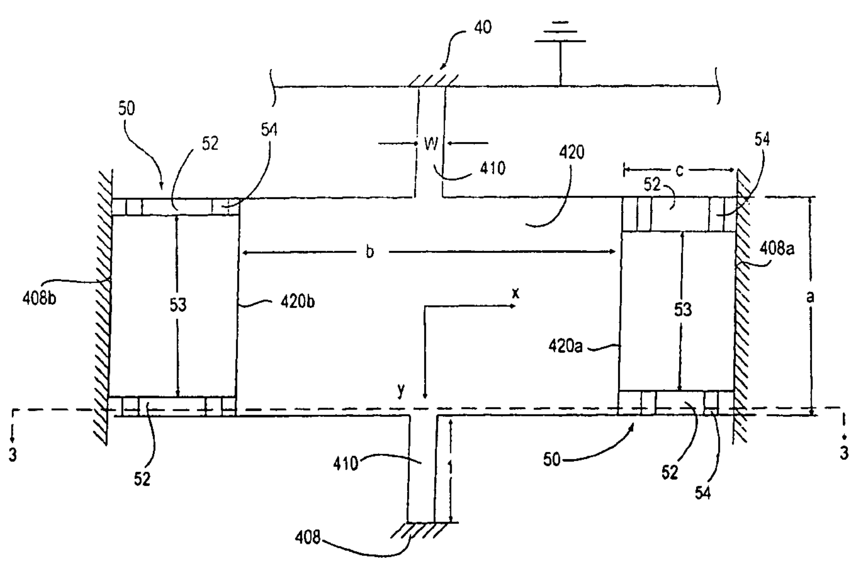
Primary Examiner—James Phan
Attorney, Agent, or Firm—Flehr Hohbach Test Albritton & Herbert LLP

[57] **ABSTRACT**

A mirror assembly of micron dimensions for use in deflecting beam of light. The mirror assembly includes a planar base and a planar mirror spaced apart from the planar base and disposed generally parallel to the planar base. The planar mirror has first and second end portions and a longitudinal axis extending between the first and second end portions. First and second torsional members extend along the longitudinal axis and are connected to the respective first and second end portions for permitting the mirror to rock between first and second positions about the longitudinal axis relative to the planar base. The first and second torsional members are secured to the planar base. At least a portion of the mirror is made from a conductive material. First and second spaced-apart electrodes are carried by the planar base for driving the mirror between the first and second positions. A tether member extends transversely of the longitudinal axis and is secured to the first torsional member and to the planar base. The tether member regulates the rocking of the mirror.

20 Claims, 12 Drawing Sheets



07/17/2002, EAST Version: 1.03.0002

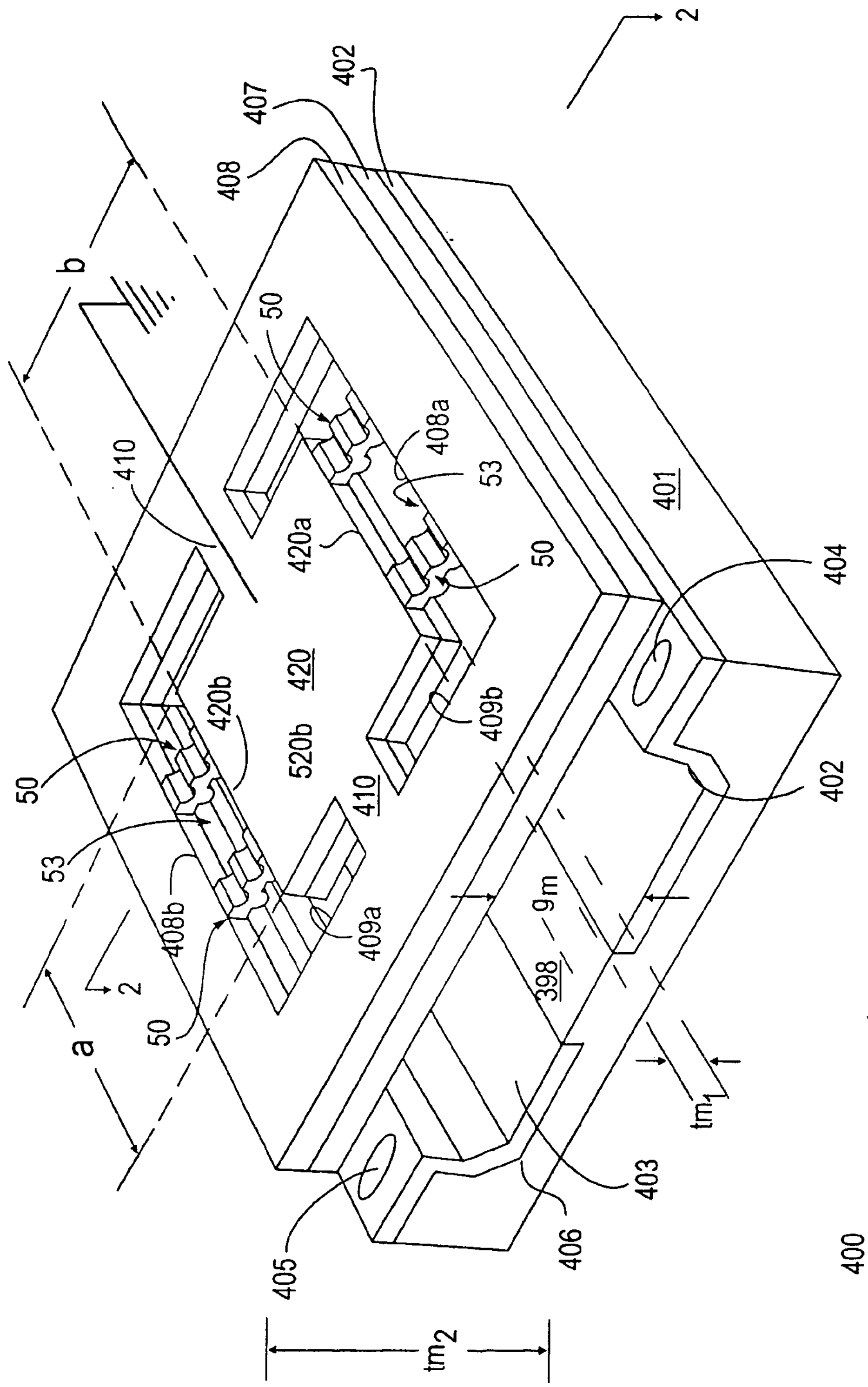
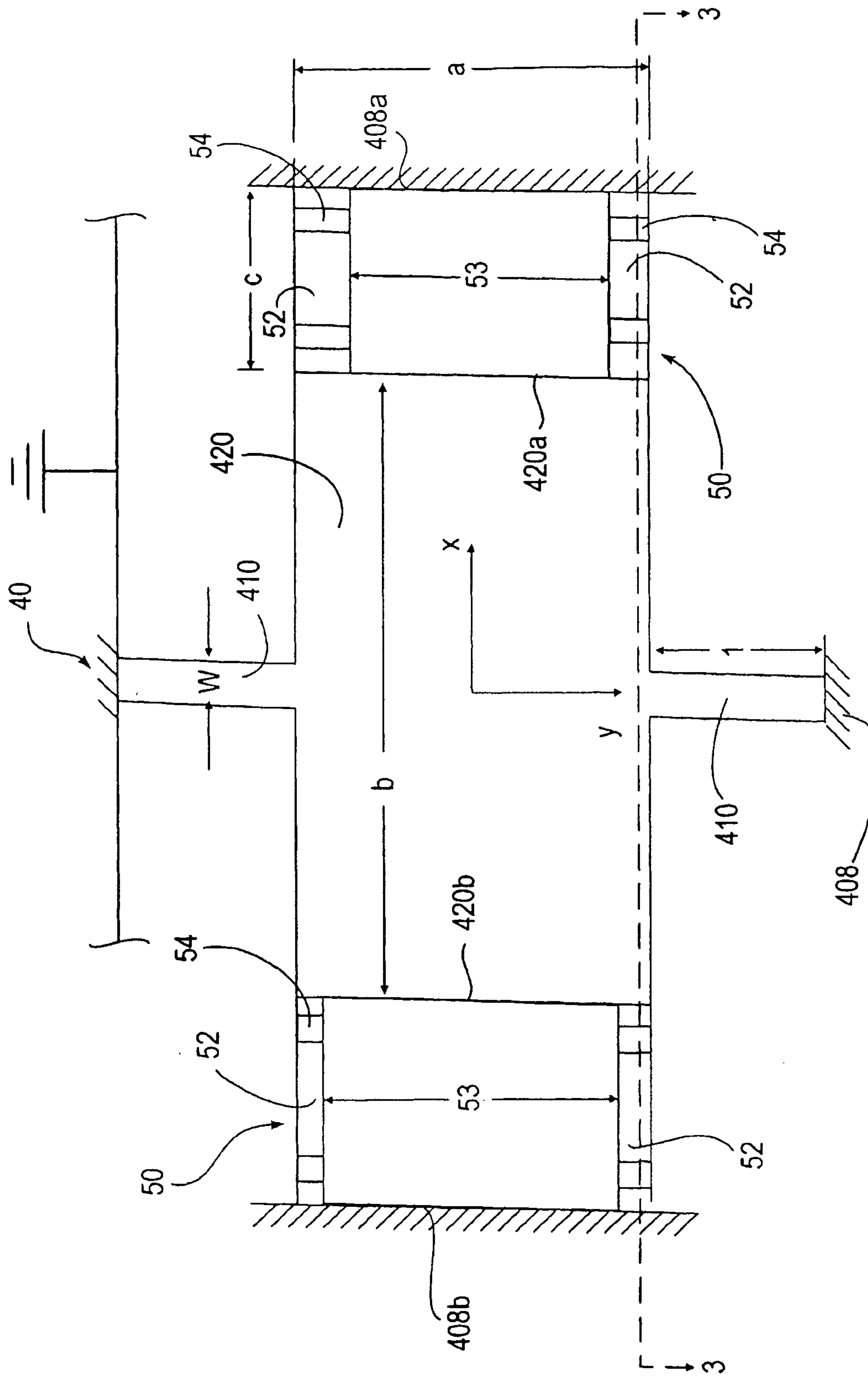

2
402
407
408
b
50
408a
53
410
420a
50
420
520b
420b
409b
401
404
402
50
53
410
408b
409a
2
a
50
g_m
398
tm_1
405
406
403
400
tm_2

Fig. 1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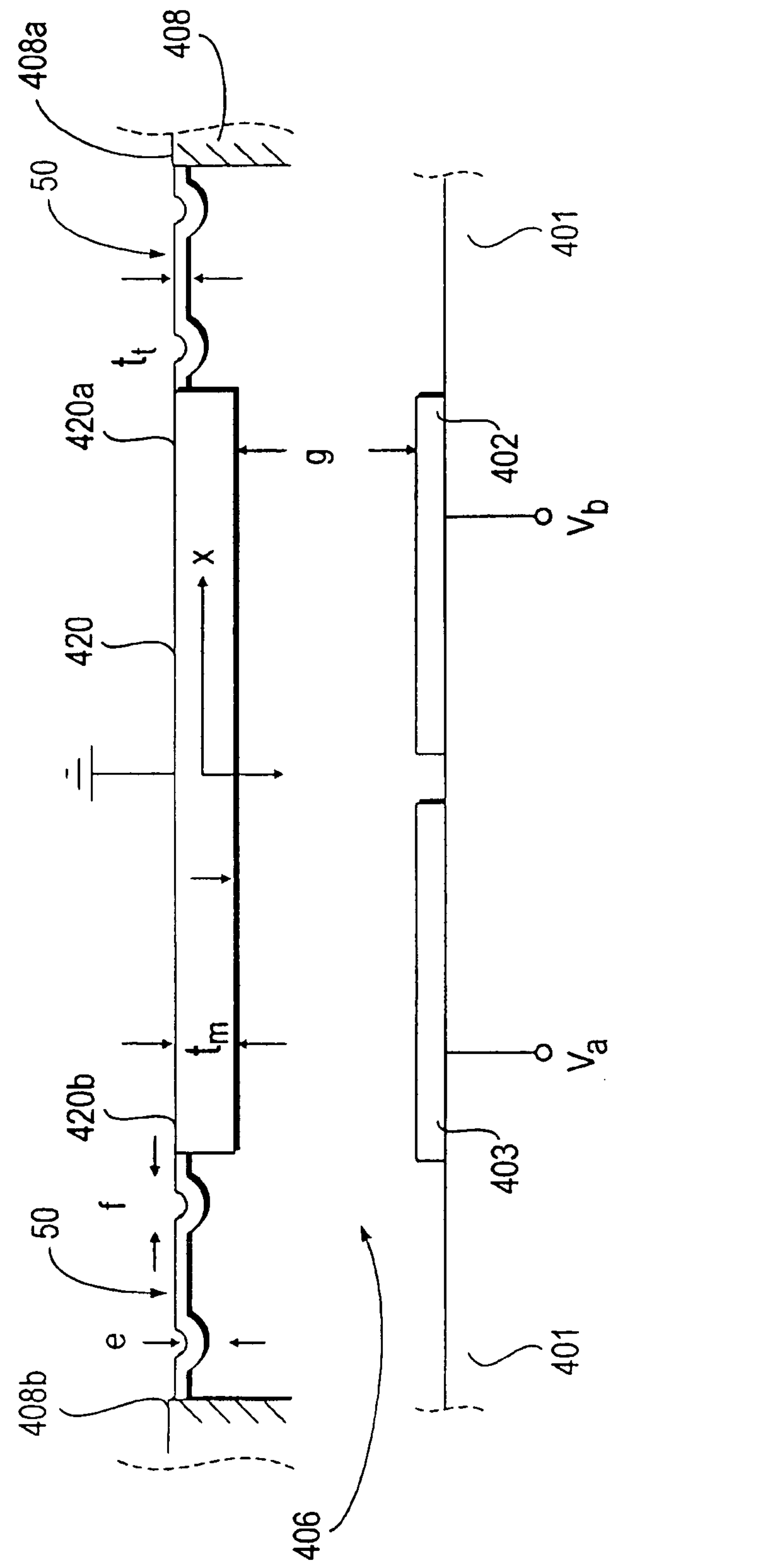
a
408a
54
c
53
54
52
52
420a
50
420
40
410
W
x
y
l
410
408
b
420b
54
52
53
50
52
408b
3

Fig. 2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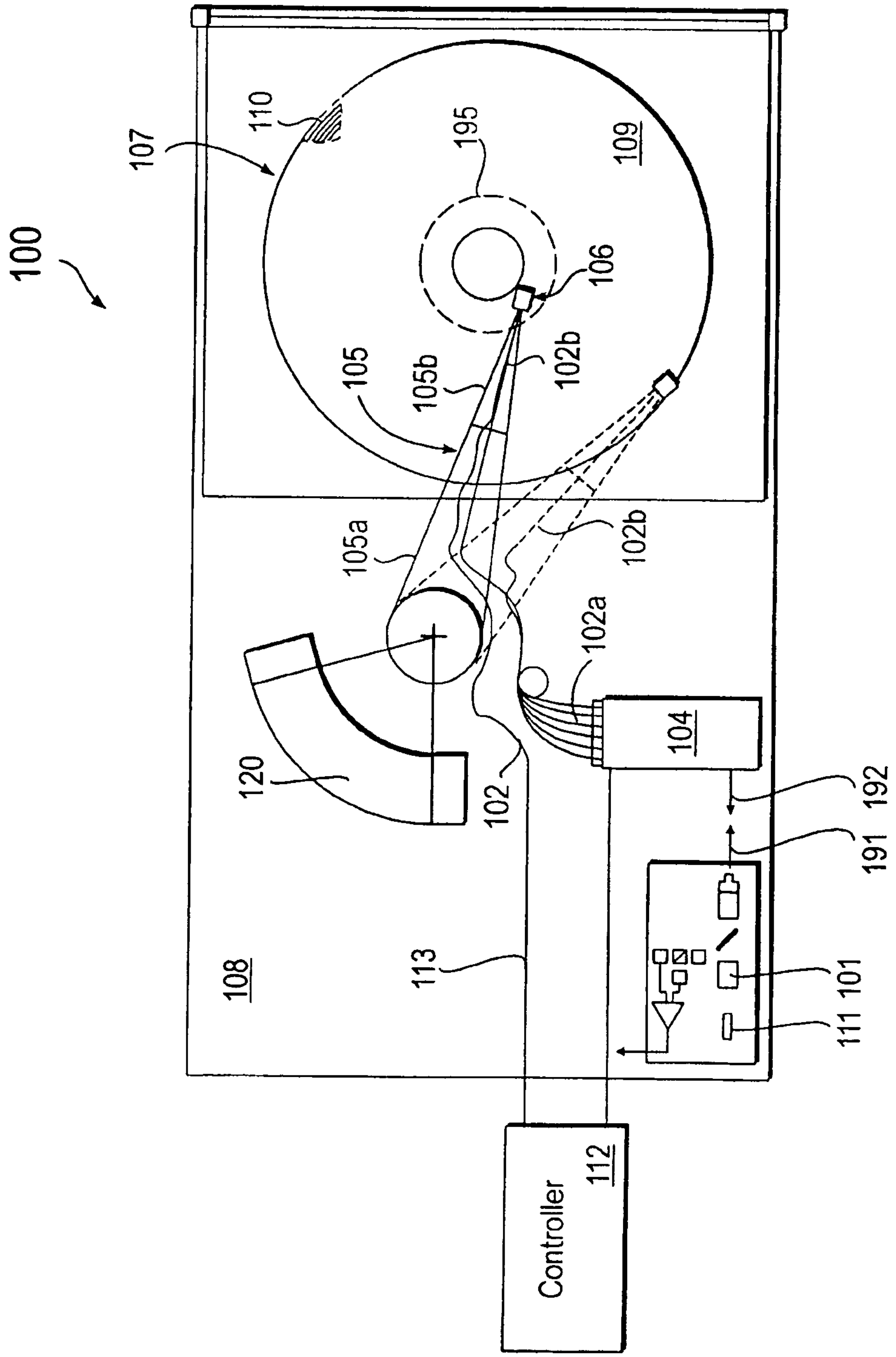
408
50
t_t
420a
g
402
V_b
x
420
401
t_m
V_a
420b
403
f
50
e
401
408b
406

Fig. 3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107
110
195
109
106
105
105b
102b
105a
102b
102a
120
102
104
192
191
101
111
113
108
Controller
112

Fig. 4

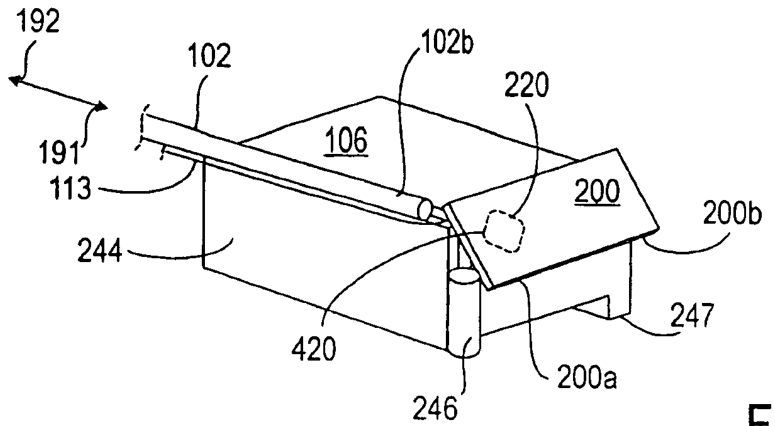


Fig. 5

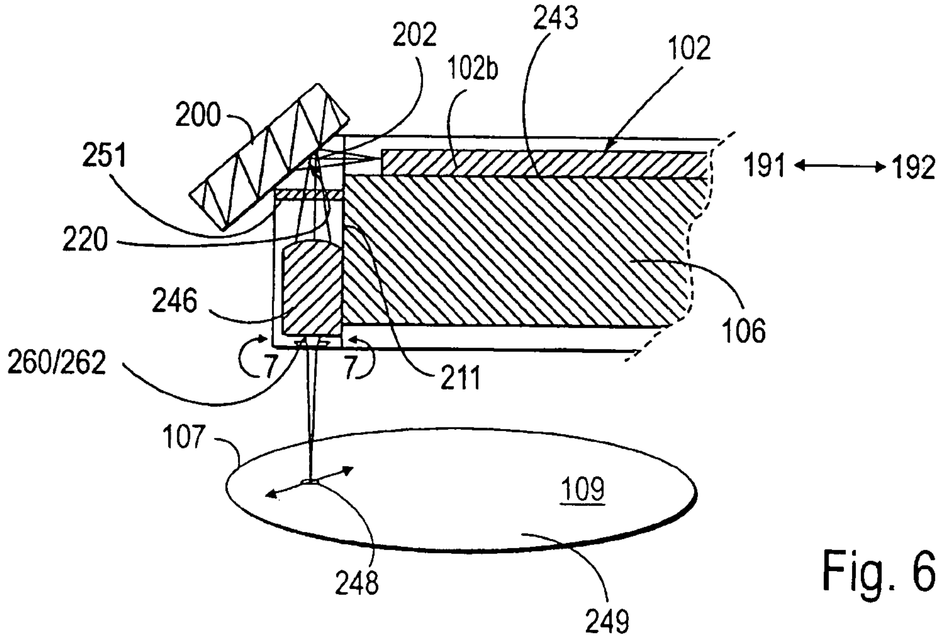


Fig. 6

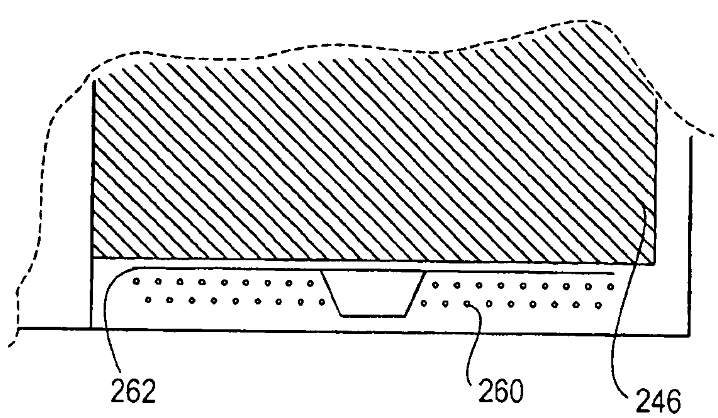
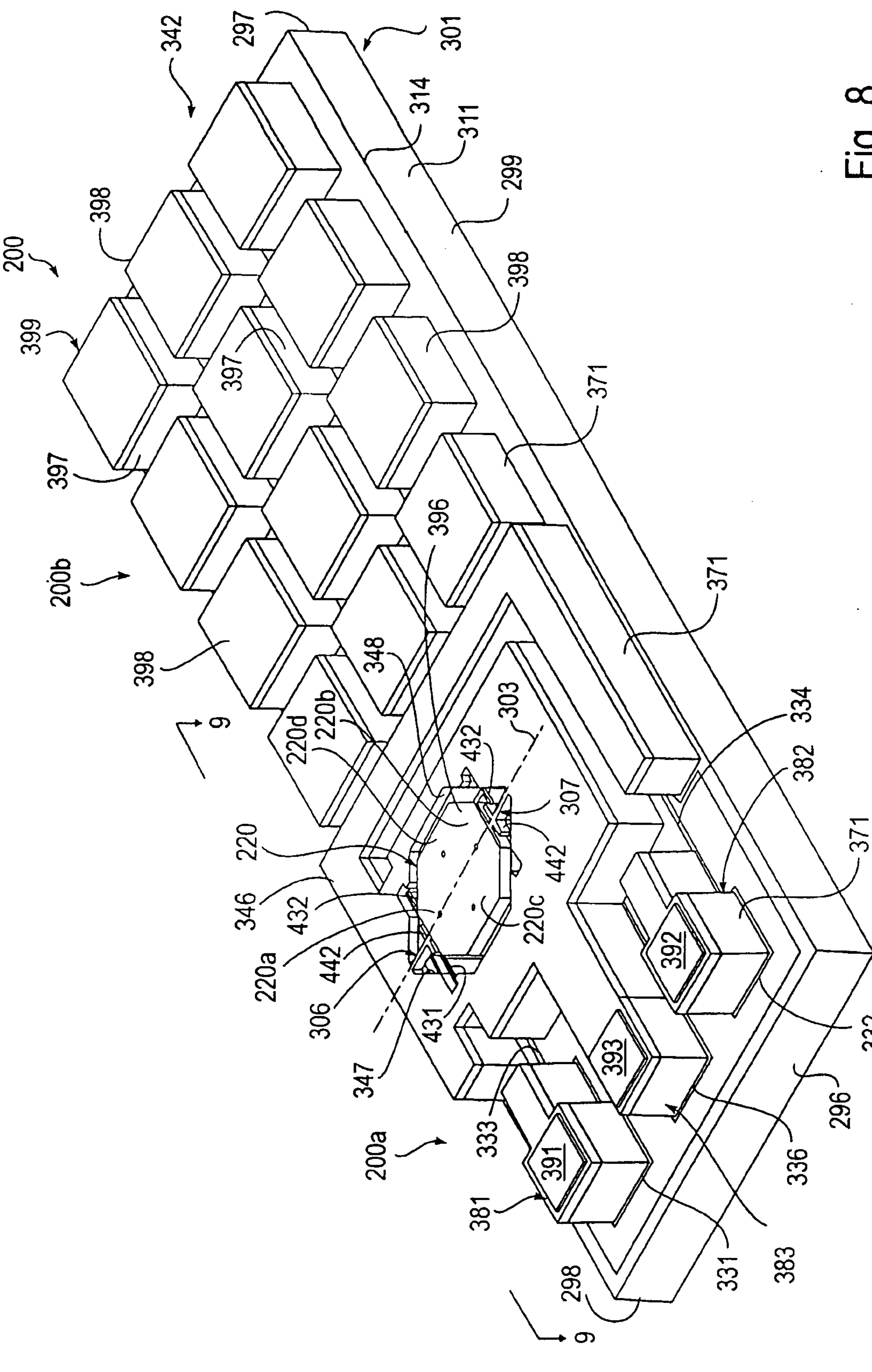


Fig. 7



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297
301
314
311
299
200
398
399
397
371
200b
396
348
303
220d
220b
432
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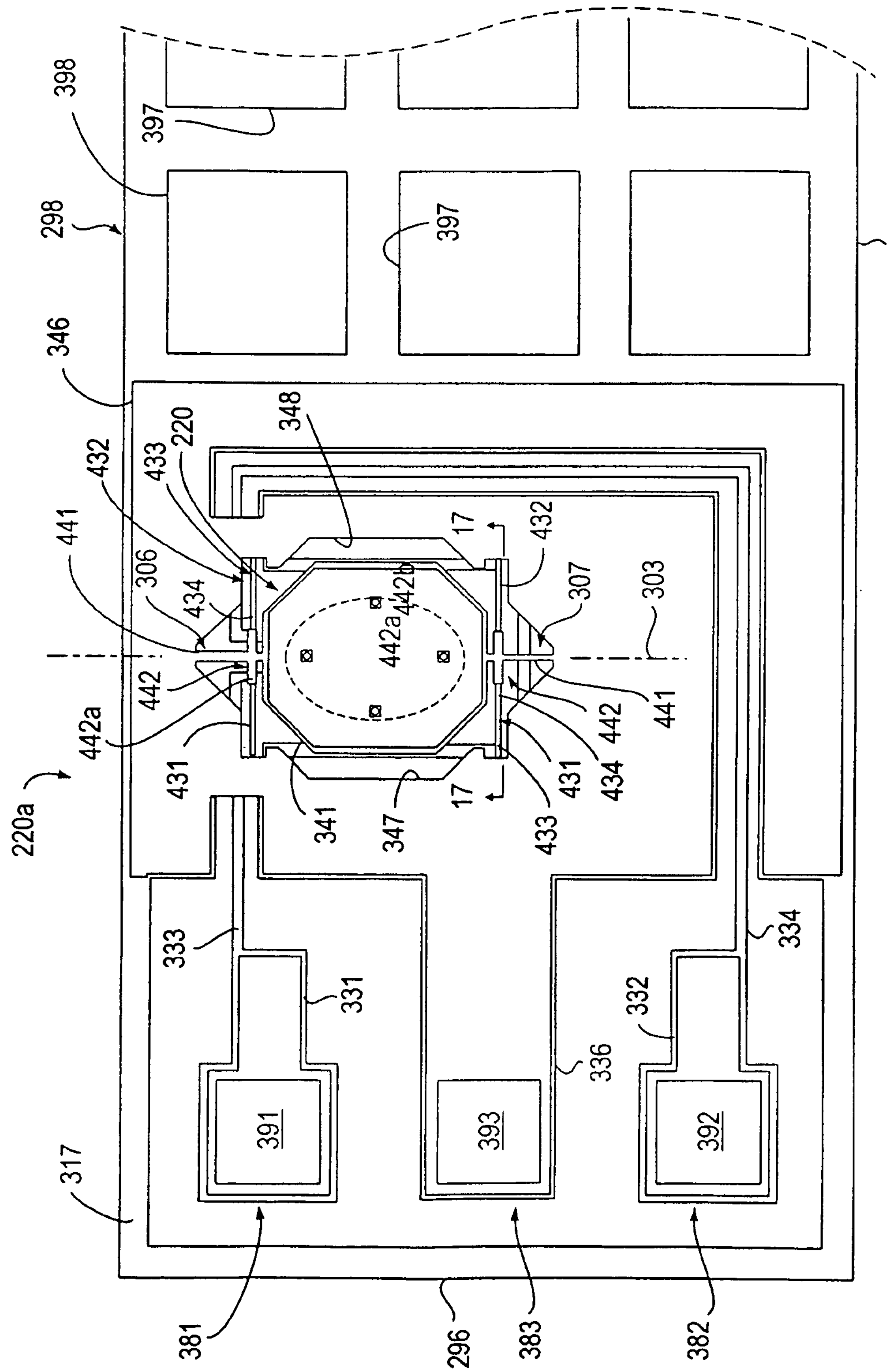
9
220
442
346
220c
220a
306
431
347
334
382
392
393
333
336
296
332
200a
391
381
331
383
298

Fig. 8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434
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442b
307
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442a
442
442a
441
442
434
431
431
220a
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433
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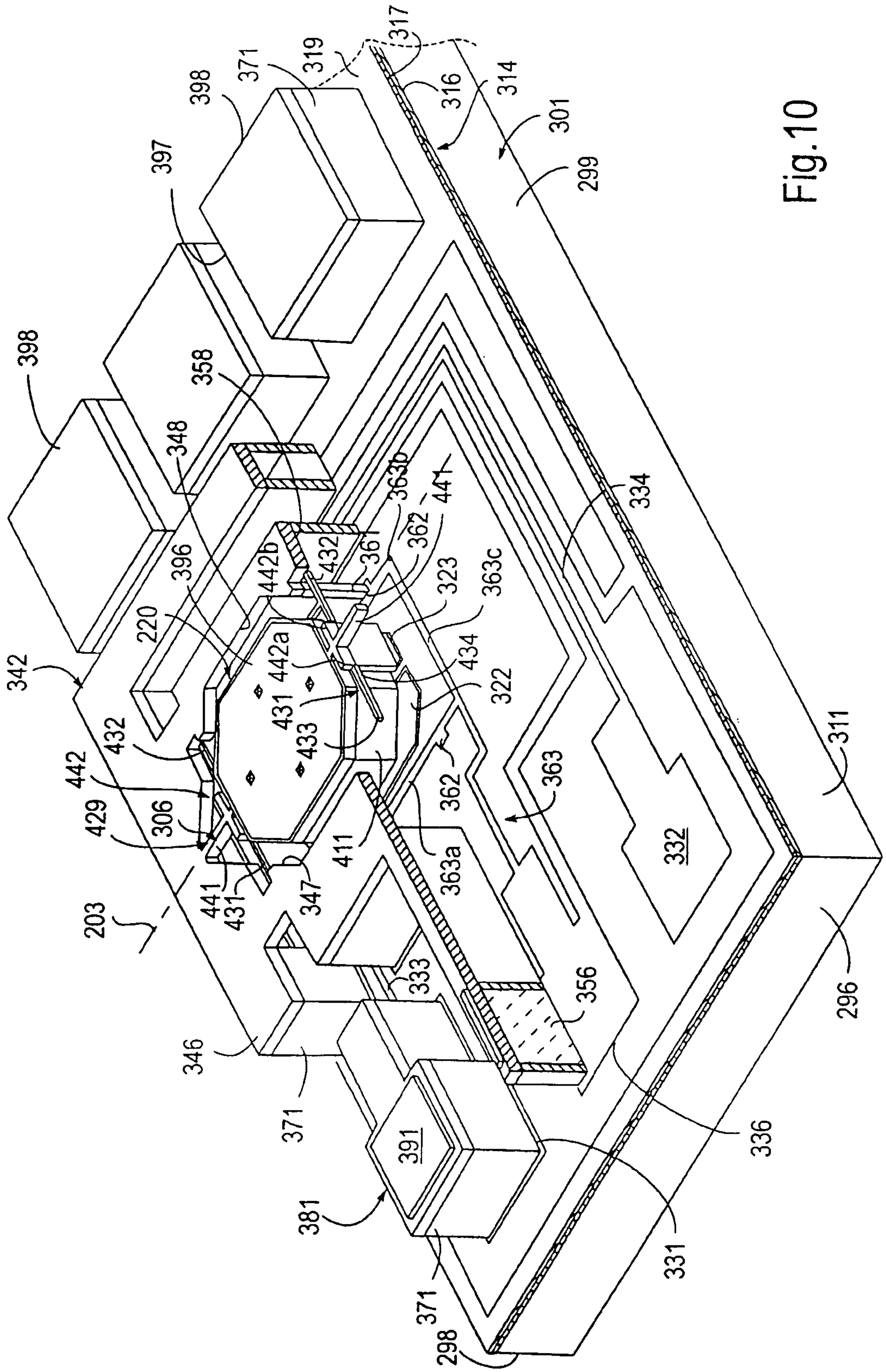
393
392
317
381
296
383
382

Fig. 9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363b
441
334
432
361
362
442b
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363c
220
442a
434
322
342
431
433
432
442
362
363
306
429
411
363a
332
311
441
431
347
203
333
356
346
371
296
336
391
381
331
371
298

Fig.10

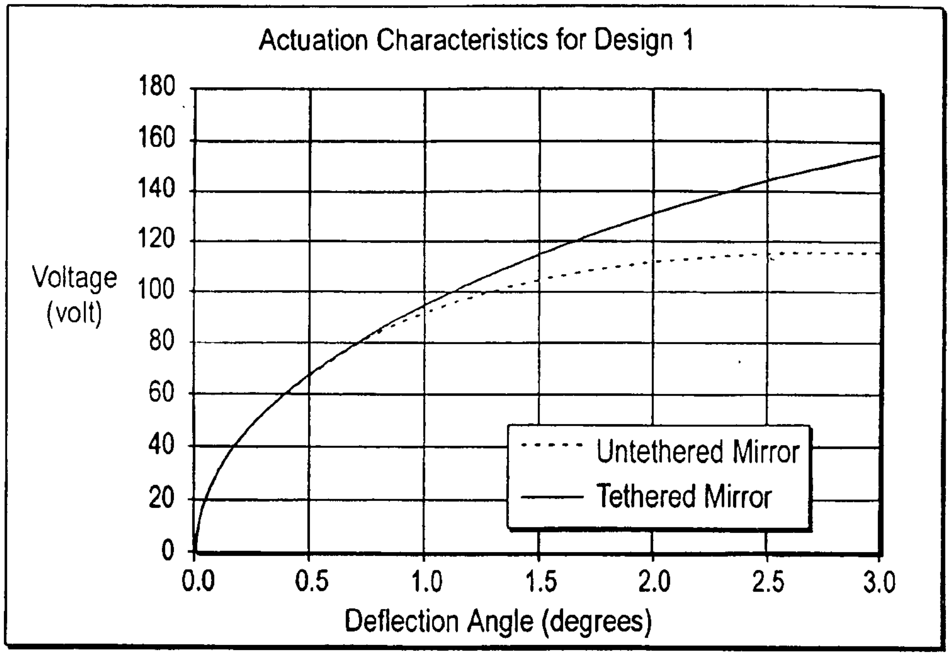
Actuation Characteristics for Design 1
Voltage (volt)
180
160
140
120
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Deflection Angle (degrees)
Untethered Mirror
Tethered Mirror

Fig. 11

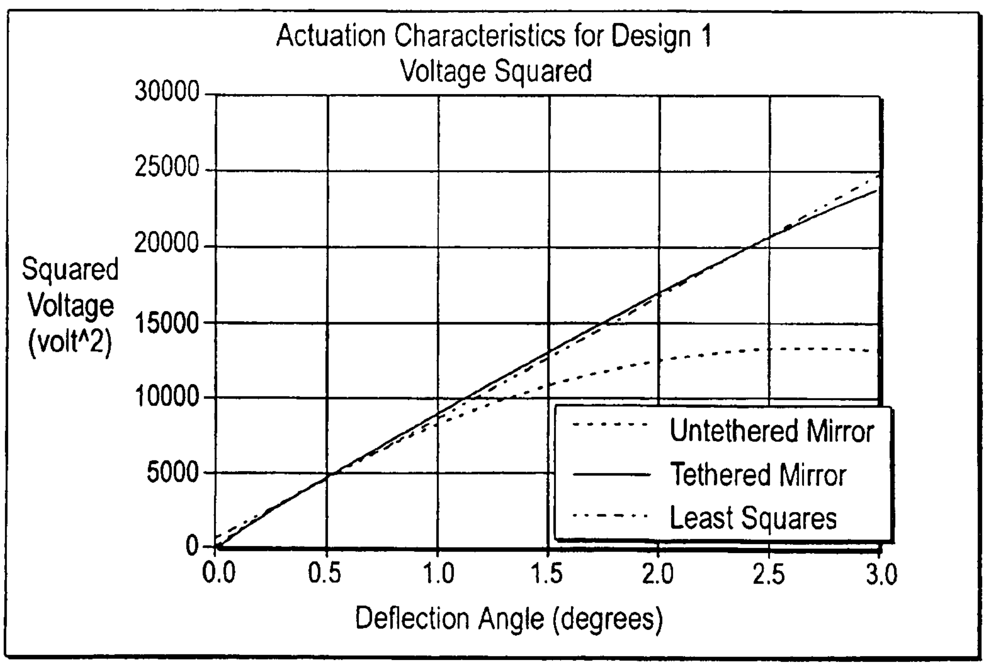
Actuation Characteristics for Design 1
Voltage Squared
Squared Voltage (volt^2)
30000
25000
20000
15000
10000
5000
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Deflection Angle (degrees)
Untethered Mirror
Tethered Mirror
Least Squares

Fig. 12

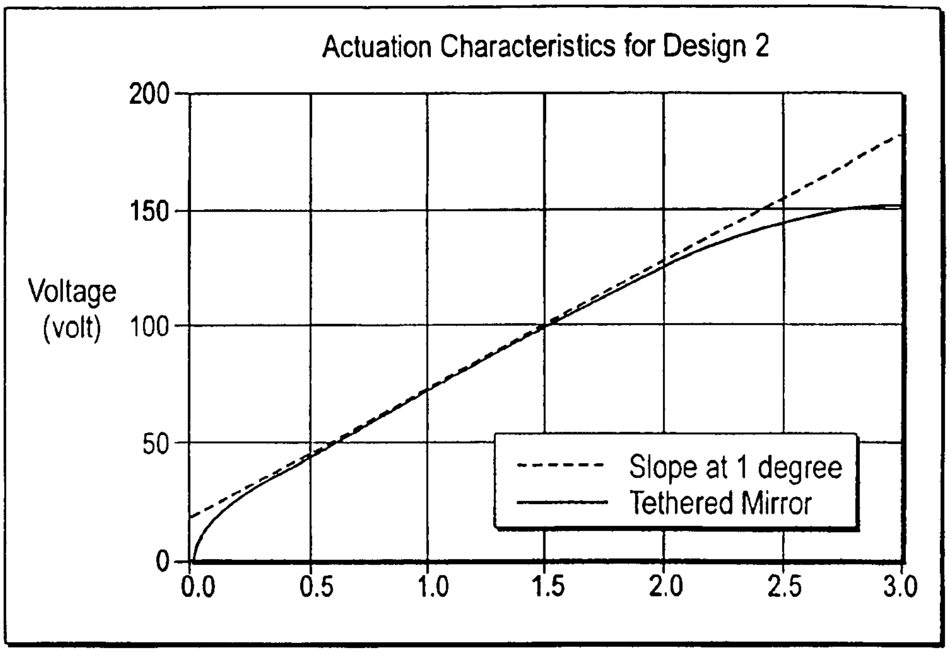

Fig. 13

Geometrical Parameter		Symbol	Value: Design 1	Value: Design 2
Hinge:	Length	L_h	50.0	50.0
	Width	W_h	3.3	2.5
	Depth	T_h	2.0	2.0
Tether:	Length	L_t	77.0	60.0
	Width	W_t	2.0	2.0
	Depth	T_t	0.5	0.2
Flange:	Length	L_f	25.0	75.0
	Width	W_f	6.0	6.0
	Depth	T_f	8.0	8.0
Plate Attach:	Length	L_p	5.0	5.0
	Width	W_p	3.3	3.5
	Depth	T_p	8.0	8.0
Linear Spring Constant		k_1	0.0092	0.0083
Cubic Spring Constant		k_3	2.6928	20.0870
Ratio of k_3 to k_1		r	293.3	2415.8

Fig. 15

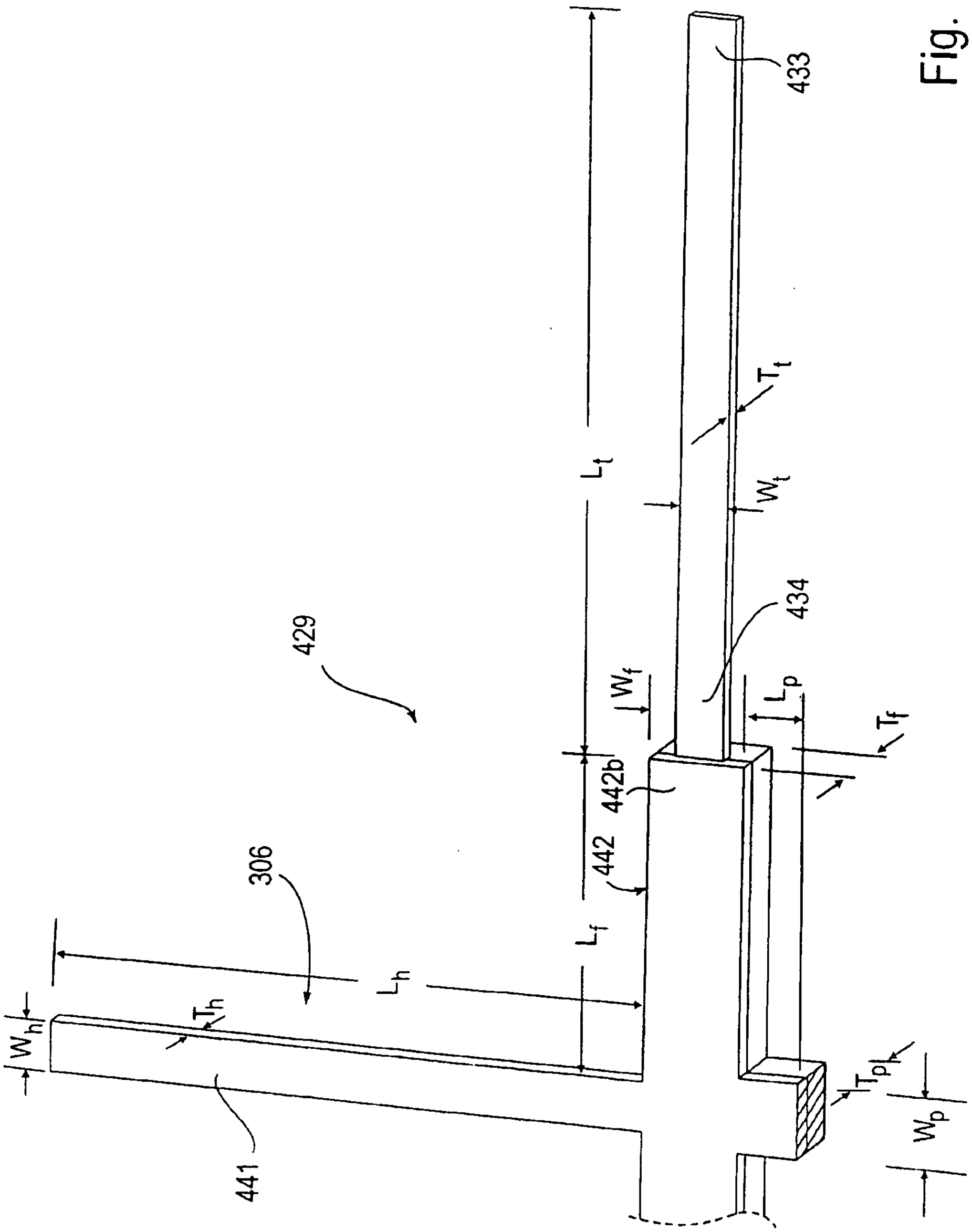

Fig. 14

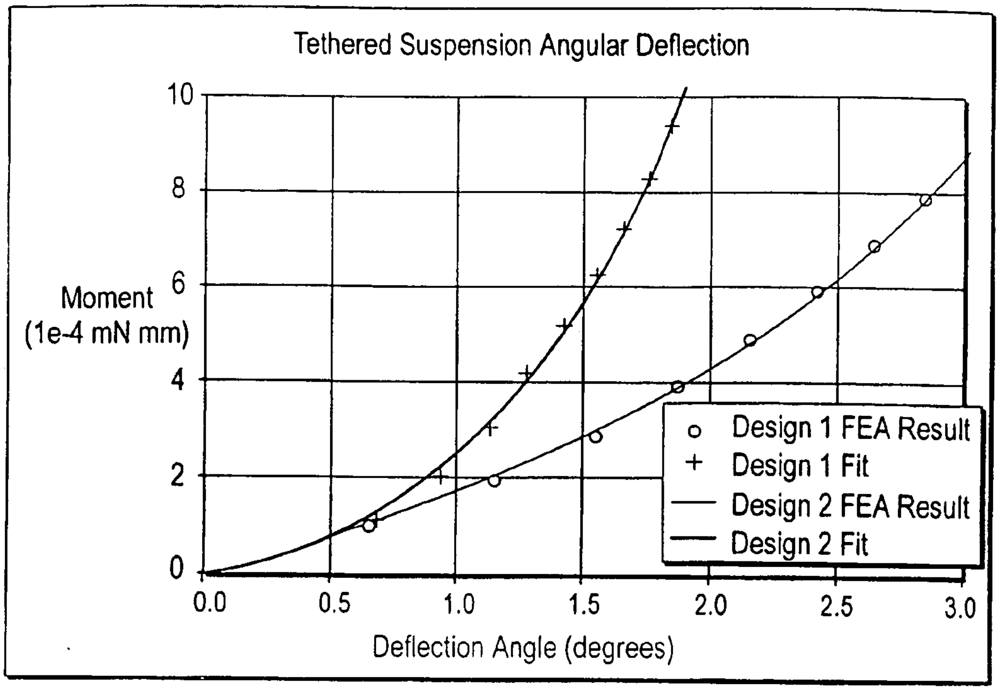

Fig. 16

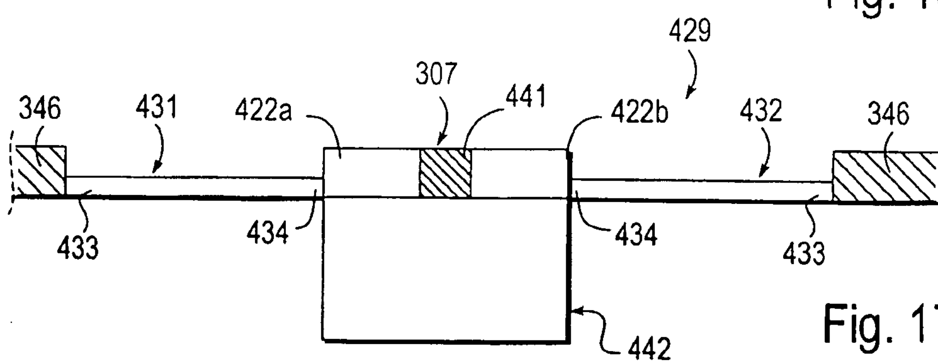

Fig. 17

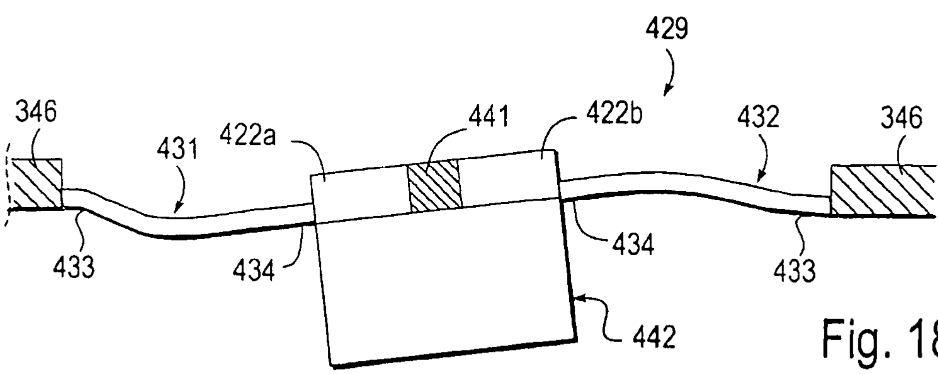

Fig. 18

MICROMACHINED MIRROR WITH STRETCHABLE RESTORING FORCE MEMBER

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. provisional patent application Ser. No. 60/100,989 filed Sep. 18, 1998 and is a continuation-in-part of U.S. patent application Ser. No. 09/231,317 filed Jan. 13, 1999, U.S. Pat. No. 5,999,303, and is a divisional of U.S. patent application Ser. No. 08/823,422 filed Mar. 24, 1997, abandoned, the entire contents of all of which are incorporated herein by this reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to micromachined mirrors for use in optical switching, steering and scanning systems and, more particularly, to micromachine mirrors for use in optical data tracking, storage and retrieval systems.

2. Background

Electrostatic pull-in is a phenomenon that limits the rang of electrostatically driven deflectable micromachined devices. In general, pull-in occurs when the nonlinear electrostatic drive overwhelms the capabilities of the device's mechanical suspension to achieve equilibrium with the electrostatic forces. In a torsional mirror, such as of the type described in copending U.S. patent application Ser. No. 09/231,317 filed Jan. 13, 1999, the electrostatic drive causes rotation of the mirror plate about the axis defined by the torsional hinge suspension. An equilibrium angular deflection is achieved when the restoring torque provided by the two torsional hinges balances the electrostatic attraction torque provided by the drive electrode. The torsional hinge suspension provides a restoring torque that is proportional to the angle of rotation of the mirror plate. However, the electrostatic torque increases nonlinearly as the separation between the drive electrode and the grounded mirror plate is decreased by the rotation of the mirror plate. At some value of angular deflection, the electrostatic torque becomes larger than what can be balanced by the linear restoring torque of the hinges. At this pull-in angle, the outer edge of the mirror plate spontaneously deflects across the remainder of the electrostatic gap thus limiting the useful angular range of the mirror to less than that which results in pull-in.

The issue of electrostatic pull-in has been presented and analyzed in several publications. For example, Seeger and Crary, *Stabilization of Electrostatically Actuated Mechanical Devices,* Proc. Transducers '97, Chicago, Ill., pp. 1133–1136, June 1997, present an approach towards preventing the pull-in phenomenon from occurring in translational electrostatic actuators. Their method places a feedback capacitor in series with the device which essentially modifies the potential energy function of the system to the point where no unstable operating points exist as the movable plate is driven towards the drive electrode. Although this method can be used to increase the stable range of torsional electrostatic devices, it has the undesirable tradeoff that the actuation voltage has to be dramatically increased in order to charge the feedback capacitor.

The issue of electrostatic pull-in for translational micromachined mirrors was discussed in Burns and Bright, *Nonlinear Flexures for Stable Deflection of an Electrostatically Actuated Micromirror,* Proc. SPIE, Vol. 3226, Austin, Tex., Sept. 1997. In this paper, a theoretical argument for the use of flexures with nonlinear deflection performance is presented. However, a design that provides for nonlinear performance is not presented. Rather, a design for a composite flexure comprising a primary and an auxiliary wherein beyond a certain deflection of the primary flexure the restoring force provided by the auxiliary flexure is combined additively to that of the primary flexure is disclosed. As such, the flexural design is piecewise linear rather than truly nonlinear.

The suspension means for both translational and torsional electrostatically actuated micromachined devices are typically modeled as slender beams or thin diaphragms. For small deflections and rotations, these structures behave linearly. Thus, the load acting on the structure is proportional to its deflection with the constant of proportionality equal to the spring constant specific to that direction of deformation. For large deflections or rotations, these structures no longer respond linearly to applied loads. The form of the nonlineality is highly dependent on the specifics of the suspension geometry but generally takes on a relationship that is approximately a superposition of the small deflection linear term together with a cubic term which dominates for the larger deflections and rotations. In Jerman, *The Fabrication and Use of Micromachined Corrugated Silicon Diaphragms,* Sensors and Actuators, A21–A23 (1990) pp. 988–992 and U.S. Pat. No. 5,116,457 for *Semiconductor Transducer or Actuator Utilizing Corrugated Supports* to Jerman, an example of such a relationship is given where thin diaphragms are used to support the central boss of a micromachined structure. However, in these references Jerman does not make productive use of the non-linear deflection characteristics of these diaphragms.

What is needed is an improved micromachined mirror assembly having a restoring torque that increases nonlinearly with the deflection angle of the mirror to compensate for the nonlinear electrostatic drive forces of the mirror assembly. Such a mirror assembly would preferably increase the pull-in angle so as to increase the effective deflection rage of the mirror.

SUMMARY OF THE INVENTION

The invention includes a mirror assembly of micron dimensions for use in deflecting a beam of light. The mirror assembly includes a planar base and a planar mirror spaced apart from the planar base and disposed generally parallel to the planar base. The planar mirror has first and second end portions and a longitudinal axis extending between the first and second end portions. First and second torsional members extend along the longitudinal axis and are connected to the respective first and second end portions for permitting the mirror to rock between first and second positions about the longitudinal axis relative to the planar base. Means is included for securing the first and second torsional members to the planar base. At least a portion of the mirror is made from a conductive material. First and second spaced-apart electrodes are carried by the planar base for driving the mirror between the first and second positions. A tether member extends transversely of the longitudinal axis and is secured to the first torsional member. Means is provided for securing the tether member to the planar base. The ether member regulates the rocking of the mirror.

BRIEF DESCRIPTION OF THE DRAWINGS

For a further understanding of the objects and advantages of the present invention, reference should be had to the following detailed description, taken in conjunction with the

accompanying drawings, in which like parts are given like reference numerals. The vertical scale of FIGS. 1–3, 8–12 and 16, where shown, has been exaggerated to facilitate understanding of the drawings.

FIG. 1 is an isometric view of a micromachined mirror assembly.

FIG. 2 is a top plan view of the micromachined mirror assembly of FIG. 1 taken along the line 2—2 of FIG. 1.

FIG. 3 is a vertical cross-sectional view of the micromachined mirror assembly of FIG. 2 taken along the line 3–3 of FIG. 2.

FIG. 4 is a top plan view, somewhat schematic, of one preferred embodiment of a magneto-optical storage system of the present invention.

FIG. 5 is an isometric view of a magneto-optical system slider head of the magneto-optical storage system of FIG. 4 having one embodiment of a steerable micromachined mirror assembly mounted thereon.

FIG. 6 is a cross-sectional view of the magneto-optical system slider head of FIG. 5.

FIG. 7 is an enlarged cross-sectional view of the magneto-optical system slider head of FIG. 5 taken along the line 7–7 of FIG. 6.

FIG. 8 is an isometric view of another embodiment of a micromachined mirror assembly suitable for use with the optical head of FIG. 5.

FIG. 9 is a top plan view of a portion of the micromachined or assembly of FIG. 8 taken along the line 9–9 of FIG. 8.

FIG. 10 is an isometric view, partially cut away, of a portion of the micromachined mirror assembly of FIG. 8.

FIG. 11 is an analytically-derived graph of actuation voltage versus deflection angle for one embodiment of the micromachined mirror assembly of present invention compared to an untethered micromachined mirror assembly.

FIG. 12 is an analytically-derived graph of the square of the actuation voltage data of FIG. 11, for both a tethered and untethered micromachined mirror assembly versus deflection angle.

FIG. 13 is an analytically-derived graph of actuation voltage versus deflection angle for another embodiment of the micromachined mirror assembly of present invention.

FIG. 14 is an enlarged view of a portion of the linear and nonlinear suspension members of the micromachined mirror assembly of FIG. 8.

FIG. 15 is a table setting forth analytically-derived dimension of the linear and nonlinear suspension members for the embodiments of the micromachined or assemblies analyzed in FIGS. 11 and 13.

FIG. 16 is an analytically derived graph of the angular deflection of the linear and nonlinear suspension members for the embodiments of the micromachined mirror assemblies analyzed in FIGS. 11 and 13 as a function of the applied moments.

FIG. 17 is a cross-sectional view of a portion of the micro-machined mirror assembly of FIG. 8 taken along the line 17—17 of FIG. 9.

FIG. 18 is a cross-sectional view of the portion of the micromachined mirror assembly of FIG. 17 in a deflected position.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

Referring in detail now to the drawings wherein similar parts of the invention are identified by like reference numerals, there is seen in FIG. 1 a micromachined mirror assembly 400 of the present invention. The steerable micromachined mirror assembly 400 includes a silicon substrate 401 that has a recess 406 therein. A spaced apart pair of planar rive (actuation) electrodes broadly and generally illustrated as 402 and 403 are disposed along the bottom of the recess 406. A planar silicon plate 407 is bonded to respective portions of the electrodes 402, 403. A planar flexure layer 408 made from a material such as silicon dioxide or silicon nitride is bonded to the outward face of the plate 407. Flexure layer 408 is formed to comprise opposed annular portions 408*a* and 408*b*.

An outward facing reflective central mirror portion 420 is defined in a portion of the top flexure layer 408 and a respective portion of the inner silicon plate layer 407 by spaced apart opposing C-shaped aperture slots 409*a*, 409*b* formed therethrough. The reflective central mirror portion 420 is configured to provide integral opposed halves or end portions 420*a* and 420*b*. The opposed halves 420*a* and 420*b* are symmetrically disposed about an distally extending from an axis formed by a pair of axially aligned, opposed flexure layer hinges 410.

The flexure layer hinges 410 are integrally formed from the fixture layer 408 and provide torsional restoring torque to the reflective central mirror portion 20. The reflective central mirror portion 420 may be metalized with gold or a similar substance to increase the optical reflectivity and to improve electrostatic actuation of the reflective central mirror portion 420.

In an exemplary embodiment, the steerable micromachined or assembly 400 operates over a bandwidth of approximately 20 to 200 KHz with an application to electrodes 402 and 403 of an actuation voltage of approximately 90 to 200 volts. The reflective central mirror portion 420 is a generally parallelogrammatic structure that includes: a linear dimension, a and b, that is approximately 300 microns or less; and a thickness, tm1, that is approximately 3 microns or less. The gap spacing between the bottom of the reflective central or portion 420 and the drive electrodes 402 and 403, gm, is approximately 10 microns or less. In the exemplary embodiment, an outside thickness of the steerable micromachined mirror assembly 400, tm2, is approximately 200 microns or less. In the exemplary embodiment, the reflective central mirror portion 420 achieves a preferable physical angular rotation of at least ±2 degrees about a longitudinal axis defined by hinges 410. Preferably, the reflective central mirror portion 420 may be driven torsionally without any excessive transverse motion and should maintain an optical flatness of lambda/10 during static and/or upon dynamic operation. The maximum stress upon electrostatic deflection should be below the expected yield stress of the material of flexure layer 408. The aforementioned characteristics and dimensions of the steerable micromachined mirror assembly 400 are meant to be exemplary in nature and should be limited by the scope of the ensuing claims only.

In an exemplary embodiment, the steerable micromachined or assembly 400 may be fabricated by etching the recess 406 into the silicon substrate wafer 401. The silicon plate 407 may be oxide bonded to achieve electrical isolation from the electrodes 402, 403 and may be subsequently thinned and polished to a desired thickness. The flexure layer 408 may be deposited and patterned to define the periphery of the reflective central mirror portion 420 and the width of the hinge 410. An isotropic etch may be used to form the aperture slots 409*a*, 409*b* around reflective central mirror portion 420 and beneath the flexure hinges 410, while leaving the silicon plate 407 under the reflective central

mirror portion **420** to provide rigid support. The etch step may be used to provide access to electrodes **402** and **403** so that the bonding pads **404** and **405** may be formed by a deposition of metal to electrically and mechanically connect to the respective electrodes **402**, **403**. While the steerable micromachined mirror assembly **400** has been described as being fabricated using bulk micromachining techniques, surface micromachining techniques may also be used, for example, surface micromachining techniques as disclosed in "Design techniques for surface micromachining MEMS processes," J. Comtois et al., 1991 SPIE Proceeding Series Volume 2639, pp. 211–222.

Referring now to FIGS. 1–3, the steerable micromachined mirror assembly **400** may include at least one tether member **50** for further coupling the reflective central mirror portion **420** to the flexure layer **408**. More specifically, the at least one tether member **50** respectively couples a respective at least one of the opposed annular portions **408***a* and **108***b* of the flexure layer **408** to the respective opposed halves **420***a* and **420***b* of the reflective central mirror portion **420**.

Each tether member **50** may be a parallelogrammatic structure **52** having at least one, preferably a pair of transverse channels **54**. As shown in FIG. 1, distal edges of opposed halves **420***a* and **420***b* each have a pair of spaced apart tethers **52** secured hereto, separated by gap **53**.

The grooves or channels **54** may be plasma etched using a planar etch to define isotropically etched contours within a selected surface area of flexure layer **408**. An etch stop may be diffused into the convoluted surface so that the etched contours follow the etch-stop layer. The flexure layer **408** portion that includes the tether member **50** may be patterned and etched from the surface opposed to that of channels **54**, with the etch stop layers producing the desired corrugated cross-section. With conventional plasma etching techniques, etched groove depths may be produced from a fraction of a micrometer to about 50 micrometer. If boron etch stops are used, the available tether member 50 thickness may range from about 0.5 micrometer to about 10 micrometer. A similar range is available with diffused electrochemical etch stops, although the maximum thickness can be increased above 20 micrometer with sufficiently long diffusions.

The tether members **50** permit torsional motion of the reflective central mirror portion **420** about axially aligned flexure layer hinges **410**, but limit transverse motion; that is, the tether member **50** limits movement of the distal edges of reflective central mirror portion **420** towards sides **408***a* and **408***b* of the flexure layer **408**. The tether member **50** also provides a torsional restoring force (in addition to that provided by flexure layer hinges **410**) to return the reflective central mirror portion **420** to an undeflected position. The tether member **50** also limits the reflective central mirror portion **420** from contacting the actuation electrodes **402** and **403** in a high drive situation, along with preventing contact deformation and warping of the reflective central mirror portion **420**. The tether member **50** further prevents the reflective central mirror portion **420** from deflecting beyond a critical angle which would otherwise result in spontaneous deflection to one of the actuator electrodes **402** or **403**.

Rotation or torsional movement of the reflective central mirror portion **420** causes the tether members **50** to deflect downwards (z-direction) while remaining attached to the sides **420***a* and **420***b* of the reflective central mirror portion **420**. In order to remain attached, tether members **50** preferably stretch somewhat to accommodate the increased distance from the sides **420***a* and **420***b* of the reflective central mirror portion **420** to the sides **408***a* and **408***b* of the flexure layer **408**.

Considering a single tether **50** acting as a beam and temporarily ignoring the presence of the grooves or channels **54** for small deflections, the amount of force required to deflect the beam in the z-direction is approximately linearly proportional to the amount of deflection realized. For larger deflections, this relationship may be non-linear, with larger incremental amounts of force required to obtain incremental deflections. The non-linearity of the tether member **50** may be tailored to meet the non-linearity in electrostatic torque caused by large angular rotations of the reflective central mirror portion **420**. Accordingly, the range of stability of the reflective central mirror portion **420** with respect to its angular deflection may be increased and a wider range of angular deflection may be realized by deterring effects of the electrostatic non-linearity for larger angular deflections.

The restoring torque available from the torsional hinges **410** alone may be insufficient at times to counteract the torque exerted by the electrostatic field at some critical rotation angle. The tether members **50** serve to provide additional restoring torque to combine with the hinge restoring torque, thus offsetting the electrostatic torque. Therefore the point of instability can be changed to occur at larger deflection angles. Also, the resonant frequency of the reflective central mirror portion **420** is preferably increased due to the additional effective torsional spring constant created by the tether members **50**. Hence, the resonant frequency is somewhat further decoupled from the actuation voltage.

In designing the tether members **50**, the non-linearity of the tether members **50** dominates at roughly the same angular deflection that causes the electrostatic force to dominate. In an embodiment where the tether members are straight beams, the tether **50** stretches significantly; therefore, the non-linearity in the deflection of the beam deflection becomes apparent for rather small reflective central mirror portion **420** angles. The use of transverse channels **54** serves to extend the linear range of the tether member **50** by allowing for the stretching to be largely accommodated by the bend in the corrugation. Onset of effective non-linearity in the tether member **50** is a function of the length c of the tether member **50**, it width d, its thickness t, the depth e, the width f and the number of corrugations. By including the transverse channels **54**, the tether member **50** further allows design flexibility in determining the onset of non-linearity. Note, however, that in certain situations the increased linear range afforded by the transverse channels **54** is undesirable in that a stronger nonlinear response is preferred. In such situations, the transverse channels **54** may be eliminated and the tether **50** takes on the shape of a flat beam. Preferably, the tether thickness t is made smaller than the thickness of the reflective central mirror portion **420** so that the non-linear force from the tether member **50** does not cause excessive warping of the reflective central mirror portion **420**.

Mirror **400** can be used with any suitable optical data storage system, such as the magneto-optical data storage and retrieval system shown in FIG. 4. In one preferred embodiment, magneto-optical (MO) data storage and retrieval system **100** includes a set of Winchester-type flying heads **106** that are adapted for use with a set of double-sided magneto-optical disks **107**, one flying head for each MO disk surface. MO disks **107** are rotatably carried in a stack by a support body **108** and for simplicity only one of the disks **107** is shown in FIG. 4. In a preferred embodiment, a set of six disks **107** are provided in a stack. Each side of a disk **107** has a planar storage surface **109** provided with a plurality of concentrically disposed data tracks **110** thereon. For simplicity, only several of the data tracks **110** are shown

in FIG. 4 and have been enlarged relative to the size of disk 107 for permitting visualization thereof.

The set of flying heads or flying MO heads 106 are coupled to a rotary actuator magnet and coil assembly 120 by an actuator arm 105 so as to be positioned over the respective planar storage surfaces 109 of the MO disks 107. Each arm 105 has a rigid proximal extremity 105a pivotably mounted on support body 108 so as to permit a distal extremity or flexible suspension 105b to pivot between a first position, shown in solid lines in FIG. 4, a second position spaced apart from the first position, shown in dashed lines in FIG. 4. It should be appreciated that the two positions shown in FIG. 4 are merely exemplary and that arms 105 are movable to any number of other positions relative to support body 108. The flying heads 106 are mounted to suspensions 105b of the arms 105.

In operation, the set of MO disks 107 are rotated by a spindle motor 195 so as to generate aerodynamic lift forces between the set of flying MO heads 106 and so as to maintain the set of flying MO heads 106 in a flying condition adjacent the respective storage surface 109. More specifically, each flying head is less than or equal to approximately 15 micro-inches above the respective upper or lower surface 109 of the set of MO disks 107. The lift forces are opposed by equal and opposite spring forces applied by the set of suspensions 105b. During non-operation, the set of flying heads 106 are maintained statically in a storage condition or position, not shown, away from the surfaces of the set of MO disks 107.

System 100 further includes a laser-optics assembly 101 and an optical switch 104 mounted on support body 108 and a set of single-mode polarization maintaining (PM) optical element or fibers 102 carried by the arms 105. Optical fibers 102 are included in the optical light emitter and receiver carried by the suspensions 105b of arms 105. In the exemplary embodiment, each of the set of single-mode PM optical fibers 102 has a proximal extremity 102a coupled to optical switch 104 and a distal extremity respectively coupled through a respective one of the set of actuator arms 105 and suspensions 105b to a respective one of the set of flying heads 106 for transmitting laser beams 191,192 between support body 108 and flying heads 106. Assembly 101 has a suitable laser source 111 such as a linearly polarized laser source, that is preferably a Fabry-Perot or a distributed feed-back (DFB)laser source, for producing an outgoing laser beam 191. Laser source 111 is selected to operate within a range of 635–685 nanometers, however a laser source of other wavelengths could also be used. Use of the optical switch 104, the set of flying heads 106, and the set of single-mode PM optical fibers 102 is described in commonly assigned U.S. patent application Ser. No. 08/844, 208 filed Apr. 18, 1997, the entire contents of which are incorporated herein by this reference. A controller 112 is electrical coupled to optical switch 104 by means of wires 113 for providing electrical command signals to the optical switch. The controller 112 is electrically coupled to optical switch 104 by means of wires 114.

Each of the flying heads 106 includes a slider body 244, an air bearing surface 247, a quarter-wave plate 251, a surface micromachined steerable mirror assembly (μMM) 200, objective optics 246, a magnetic coil 260 and a yoke 262 (see FIGS. 2–4). The flying head 106 and the slider body 244 are dimensioned to accommodate the working distances between the objective optics 246, the single-mode PM optical fiber 102 and the reflective substrate or mirror assembly 400. Although slider body 244 may include industry standard "mini", "micro", "nano", or "pico" sliders, alternatively dimensioned slider bodies 244 may also used, as determined by the aforementioned dimensional constraints of the elements used with the flying MO head 106. Accordingly, in the preferred embodiment, the slider body 244 comprises a mini slider height (889 um) and a planar footprint area corresponding to that of a nano slider (1600×2032 um).

The single-mode PM optical fiber 102 is coupled to the slider body 244 along an axial cutout 243 and the objective optics 246 is coupled to the slider body 244 along a vertical corner cutout 211. Although in the preferred embodiment the axial cutout 243 is located along a periphery of the slider body and the vertical cutout 211 is located at a corner of the slider body 244, the axial cutout 243 and the vertical cutout 211 may be located at other positions on the flying head 106, for example between the periphery and a central axis or alternatively along the central axis itself. Those skilled in the art will recognize that positioning the optical fiber 102 and the objective optics 246 at other than along a central axis may function to affect a center of mass of the magneto-optical head 106 and thus its flying dynamics. Accordingly, the point of attachment of the flying MO head 106 to the suspension may require adjustment to compensate for off-center changes in the center of mass of the magneto-optic head 106. Preferably, the cutouts 243 and 211 may be designed as channels, v-grooves or any other suitable configuration for coupling and aligning the single-mode optical fiber 102 and objective optics 246 to the flying head 106.

Mirror assembly 400 can be attached to slider body 244 in the same manner that an alternate mirror assembly 200 is shown attached to slider body 24 in FIG. 5. As more fully discussed below, mirror assembly 200 includes a small reflective mirror 220, shown in FIG. 5 on a side of the mirror assembly 200 opposite to that which is visible and thus illustrated in dashed lines. In the preferred embodiment, outgoing laser beam 191 and incoming or return laser beam 192 traverse an optical path to and from the surface recording layer 245 on surface 109 of the MO disk 107 that includes the single-mode PM optical fiber 102, the mirror assembly 200, the quarter-wave plate 251 and the objective optics 246. The outgoing laser beam 191 is emitted from optical fiber distal extremity 102b as a Gaussian beam.

During writing of information, the outgoing laser beam 191 is selectively routed by the optical switch 104 to the MO disk 107 so as to lower a coercivity of the recording/storage layer 249 by heating a selected spot of interest 248 to approximately the Curie point of the recording/storage layer 249. Preferably, the optical intensity of outgoing laser beam 191 is held constant, while a time varying vertical bias magnetic field is created by coil 260 to define a pattern of "up" or "down" magnetic domains perpendicular to the MO disk 107. This technique is known as magnetic field modulation (MFM). Subsequently, as the selected spot of interest 248 cools, information is encoded within the recording/storage layer 249 of the respective spinning disk 107.

During readout of information, the outgoing laser beam 191 (at a lower intensity compared to writing) is selectively routed to the MO disk 107 such that at any given spot of interest 248, the Kerr effect causes (upon reflection of the outgoing laser beam 191 from the recording/storage layer 249) a reflected laser beam 192 to have a rotated polarization of either clockwise or counter clockwise sense that depends on the magnetic domain polarity at the spot of interest 248.

The aforementioned optical path is bidirectional in nature. Accordingly, the reflected laser beam 192 is received through the flying head 106 and enters the distal end 102b

microns and preferably approximately 50 microns and a width ranging from 1 to 8 microns and preferably approximately three microns.

At least one patterned layer of any suitable sacrificial material such as phosphosilicate glass (PSG) is disposed between the patterned portions of plate layer 342 and planar base 301. Such PSG or spacer layer 356 is disposed atop layer 319 and has a thickness ranging from 8 to 13 microns and preferably approximately 10 microns. PSG layer 356 is removed below mirror platform 341 and a portion of frame 346 to provide a space or chamber 358 inside mirror assembly 200 (see FIG. 10). Chamber 358 extends to polysilicon layer 319 and the exposed portions of planar base 301 in these areas. As such, mirror platform 341 is spaced apart from dielectric layer 314 and spaced above first and second drive electrodes 322 and 323. The drive electrodes are exposed to the bottom of the mirror platform 341.

Means is included within mirror assembly 200 for securing frame 346 and first and second hinges 306 and 307 interconnecting frame 346 and mirror platform 341 to planar base 301. In this regard, a plurality of posts 361 extend perpendicularly between the underside of the frame and the planar base for anchoring the plate layer 342 to the planar base 301. One of such posts 361 is shown in FIG. 10. Posts 361 are each made from any suitable material and in the embodiment illustrated are made from a conductive material. More specifically, posts 361 are made from polysilicon and are secured to plate layer 342. Each of the posts 361 rests on a landing pad 362 formed from polysilicon layer 319 and electrically coupled to ground conductive pad 336 by a conductive trace 363 also formed from the polysilicon layer 319. First and second portions 363*a* and 363*b* of ground trace 363 extend respectively along the length of the outer sides of first and second drive electrodes 322 and 323. A third portion 363*c* the trace 363 extends perpendicularly between portions 363*a* and 363*b* adjacent second end portions 322*b* and 323*b* of the drive electrodes 322 and 323. The means for securing or anchoring frame 346 to planar base 301 further includes a plurality of wall-like members or walls 371 extending between plate layer 342 and the planar base 301 (FIGS. 8 and 10). Walls 371 are each made from any suitable material such as a conductive material. More specifically, the walls 371 are made from polysilicon and are secured to plate layer 342. Each of the walls sits on a pattered portion of polysilicon layer 319.

Plate layer 342 and walls 371 further serve to form a plurality contact platforms 381, 382 and 383 for providing electrical signals to respective conductive or interconnect pads 331, 332 and 336. A thin layer of at least one conductive material is deposited on the top of platforms 381–383 by any suitable means to provide respective first and second contact pads 391 and 392 and ground contact pad 393 thereon. Each of such contact or bond pads preferably consists of a thin layer of chromium disposed on plate layer 342 and having a thickness of approximately 10 nanometers and a thicker layer of gold having a thickness of approximately 500 nanometers placed on top of the chromium layer. Ground contact pad 393 is used to ground mirror platform 341.

A thin layer 396 is placed or deposited on top of mirror platform 341 for providing a surface of optical quality. Layer 396 is comprised of one or more thin layers of material that in combination create high reflectivity at the wavelength of the laser light. Specifically, layer 396 includes a thin layer of chromium having a thickness of approximately 5 nanometers deposited on the top of mirror platform 341 by any suitable means. A thicker layer of gold having a thickness of approximately 100 nanometers is deposited on top the chromium layer by any suitable means and is further included in the thin layer 396.

Slider attach area 200*b* of mirror assemblies 200 occupies approximately one half of mirror assembly 200 (See FIG. 8). The slider attach area has a grid of longitudinally and transversely aligned grooves or permanent channels 397 to provide a plurality of plateaus or mesas 398. Plate layer 342 has another portion or remainder portion 399 which forms the top surface of mesas 398 and walls 371 form the sides of the mesas. Mesas 398 are each suitably shaped and dimensioned in plan and in the embodiment illustrated are each square shaped in plan with dimensions of approximately 150 microns by 150 microns.

A plurality of ribs 411 are secured to the bottom of mirror platform 341 for providing rigidity to mirror 220. The ribs 411 are made from any suitable material and preferably made from the same conductive material which forms posts 361 and walls 371. As such, the ribs 411 are made from polysilicon. Ribs 411 extend perpendicular to the bottom of platform 341 toward planar base 301 and preferably extend at least halfway between the mirror platform 341 and planar base 301. A peripheral rib 411 extends completely around the perimeter of the octagonally-shaped mirror platform 341. One or more additional ribs can optionally be provided within the peripheral rib 411. In one preferred embodiment of mirror assembly 200, crossed internal ribs 411 of the type shown in FIG. 10 of copending U.S. patent application Ser. No. 09/192,006 filed Nov. 13, 1998 [File No. A-66166-1] and described therein are additionally provided. The bottom surface of mirror platform 341 is spaced apart from the to surface of first and second drive electrodes 322 and 323 a distance ranging from 4 to 12 microns and preferably approximately 10 microns to provide an air gap between the ribs 41 and the electrodes 322 and 323. The ribs each 411 have a width ranging from 2 to 6 microns and preferably approximately 4 microns and a depth ranging from 4 to 8 microns and preferably approximately 6 microns.

Mirror assembly 200 has means which includes linear and nonlinear suspension 429 for providing a mechanical restoring force that is responsive to the electrostatic force provided by first and second drive electrodes 322 and 323. The linear means or component of suspension 429 includes first and second torsional hinges 306 and 307 for providing a component to such mechanical restoring force that increases linearly with the deflection angle of first and second hinges 306 and 307 and mirror 220. Suspension 429 further includes a nonlinear means or suspension, that is a suspension of any type which provides a restoring force that increases nonlinearly with the deflection angle of first and second hinges 306 and 307 and mirror 220. In this regard, first and second tether members 431 and 432 are secured to at least one of first and second torsional hinges 306 and 307. More specifically, a set of first and second stretchable or tether members or tethers 431 and 432 are preferably secured to each of the first and second torsional hinges 306 and 307 (see FIGS. 9 and 10). The relative magnitudes of the nonlinear component of the restoring torque to the linear component is largely a function of the length, width, and thickness of the tether members 431 and 432.

Each of the flexural members or tethers 431 and 432 is preferably formed integral with plate layer 342. As such, each of the elongate tethers 431 and 432 has an outer end 433 joined to frame 346. In this manner, the frame 346 is included within the means of mirror assembly 200 for securing each of tethers 431 and 432 to planar base 301. Each of the elongate tethers 431 and 432 has an opposite

of the single-mode PM optical fiber **102**. The reflected laser beam **192** propagates along the single-mode PM optical fiber **102** to exit at its proximal end **102***a* and is selectively routed by the optical switch **104** for transmission to laser-optics assembly **101** for subsequent conversion to an electrical signal.

Micromachined mirror assembly or mirror assembly **200** cm be of the type disclosed in copending U.S. patent application Ser. No. 09/192,006 filed Nov. 13, 1998 [File No. A-66166-1], the entire contents of which are incorporated herein by this reference. Mirror assembly **200** has a size and shape similar to a semiconductor chip and is of micron dimensions. Mirror assembly **200** has first and second extremities or end portions **200***a* and **200***b* and has first and second parallel sides **296** and **297** forming the end surfaces of the extremities **200***a* and **200***b* and third and fourth parallel sides **298** and **299** extending between the extremities **200***a* and **200***b* (see FIG. **8**). First end portion **200***a* is referred to as working area **200***a* and second end portion is referred to as slider attach area **200***b* herein. Mirror assembly **200** can have a length between sides **296** and **297** ranging from 500 to 3000 microns and preferably approximately 1850 microns, a width between sides **298** and **299** ranging from 300 to 1000 microns and preferably approximately 650 microns and a height between its top and bottom surfaces ranging from 75 to 600 microns and preferably approximately 175 microns.

Mirror assembly **200** has a planar base **301**. Planar mirror **220** is spaced apart from and parallel to the planar base **301** and has first and second end portions **220***a* and **220***b* and a central longitudinal axis **303** extending between such end portions (see FIGS. **8–10**). The longitudinal axis **303** extends through the center of mirror **220** and perpendicular the longitudinal axis of mirror assembly **200**. Mirror further includes first and second halves symmetrically disposed on longitudinal or rotational axis **303**.

First and second torsional members **306** and **307** are secured to respective first and second end portions **220***a* and **220***b* of mirror **220**. The torsional members or hinge members **306** and **307** each extend along longitudinal axis **303** and permit the mirror **22** to rock about longitudinal axis **303** between first and second deflected positions relative to planar base **301**. The mirror **220** passes through its home or planar position, shown in FIGS. **8–10**, as it travels between its first and second deflected positions. Securing means, as more fully discussed below, is included within mirror assembly **200** for securing the first and second hinge members or hinges **306** and **307** to planar base **301**.

Planar base **301** has a first or substrate layer **311** which serve as the rigid support for the laminar structure of mirror assembly **200**. Substrate **311** has the shape of a parallelepiped. Substrate **311** has a length and width which define the length and width of mirror assembly **200** and has a thickness ranging from 75 to 600 microns and preferably approximately 175 microns. The relatively thick substrate can be formed from any suitable material such as silicon, quartz and other relatively high-temperature glasses and in a preferred embodiment substrate **311** is formed from N-type silicon in wafer form.

A layer **314** formed from at least one layer of a dielectric material overlies the substrate **311** and is included in planar base **301** (see FIG. **10**). In one preferred embodiment of mirror assembly **200**, dielectric layer **314** is a laminate which includes a thin layer of silicon dioxide **316** disposed atop substrate **311** and a thin layer **317** of any suitable acid etch-resistant dielectric material, preferably a hydrofluoric acid-resistant dielectric material such as silicon nitride, overlying the silicon dioxide layer **316**. Silicon dioxide layer **316** has a thickness ranging from 300 to 500 nanometers and preferably approximately 300 nanometers. Silicon nitride layer **317** has a thickness ranging from 200 to 300 nanometers and preferably approximately 250 nanometers. The dielectric layer **314** can alternatively consist solely of a layer of silicon nitride. In other embodiments of mirror assembly **200**, the dielectric layer **314** can consist of one or more layers of any other suitable dielectric material.

A patterned layer **319** made from any suitable conductive material such as polysilicon is disposed atop dielectric layer **314** (see FIG. **10**). Planar polysilicon layer **319** has a thickness ranging from 100 to 300 nanometers and preferably approximately 250 nanometers. The patterned layer **319** has spaces therein to form, among other things, first and second drive electrodes **322** and **323** which in the finished mirror assembly **200** are spaced below mirror **220**. First and second electrodes **322** and **323** have an aggregate shape in plan which is octagonal and approximates the octagonal shape of mirror **220**. Such aggregate octagonal shape of drive electrode **322** and **323** is smaller than the octagonal shape of mirror **220**. First and second conductive pads **331** and **332** and first and second conductive traces **333** and **334** are formed by polysilicon layer **319** on planar base **301**. A first electrical trace **333** extends from first conductive pad **331** to first drive electrode **322** and a second electrical trace **334** extends from second conductive pad **332** to the second drive electrode **323**. A third conductive pad **336** is formed by polysilicon layer **319** between first and second conductive pads **331** and **332**.

Working area **200***a* of the mirror **220** includes a mirror platform **341** formed from an upper layer **342** of material spaced above and parallel to planar base **301** (see FIGS. **8–10**). First and second hinges **306** and **307** are also formed from plate layer **342** and are each secured to the mirror platform **341** at one end and the inner edges of the frame **346** at the other end. A peripheral portion or frame **346** formed from upper layer **342** extends around mirror platform **341**. Frame **346** is disposed in working area **200***a* and is provided with first and second substantially C-shaped apertures **347** and **348** extending therethrough for forming mirror platform **341** and first and second hinges **306** and **307**. More specifically, apertures **347** and **348** have shapes resembling parentheses. Apertures **347** and **348** are symmetrically disposed about central longitudinal axis **303**. Upper layer **342** is made from any suitable conductive material such as polysilicon and has a thickness ranging from 1.5 to 2.5 microns and preferably approximately 2.0 microns. Frame **346** has a length measured perpendicular to mirror axis **303** ranging from 400 to 700 microns and preferably approximately 580 microns and a width ranging from 400 to 650 microns and preferably approximately 650 microns.

The conductive mirror platform **341** serves as an additional or ground electrode and has a shape in plan which is substantially elliptical and more specifically octagonal. The elongated octagonal shape of mirror platform **341** and mirror **220** is at least a large as the spot, shown in phantom lines in FIG. **9**, created thereon when mirror **220** is disposed at an angle of 45° in the path of laser beams **191**,**192**. The mirror platform has a length at its center along central longitudinal axis **303** ranging from 170 to 250 microns and preferably approximately 220 microns and a width at its center extending perpendicular to longitudinal axis **303** ranging from 140 to 200 microns and preferably approximately 170 microns. First and second hinges **306** and **307** each have a length measured along longitudinal **303** ranging from 15 to 60

inner end **434** coupled to the respective hinge **306** or **307**. As shown most clearly in FIGS. **9** and **10**, each of the torsional hinges **306** and **307** is formed with an elongate portion **441** which extends along longitudinal axis **303** between mirror platform **341** and frame **346** and is optionally formed with a flange portion or flange **442** formed integral with elongate portion **441** and extending transversely thereof. Flange **442** has a first end **442***a* spaced outwardly from elongate portion **441** and a second end **442***b* spaced outwardly from the elongate portion opposite of first end **442***a*. Inner end **434** of first tether **431** is secured to first end **442***a* of the flange **442** and inner end **434** of second tether **432** is secured to second end **442***b* of the flange. As so formed, flange **442** and the first and second tethers **431** and **432** secured thereto extend along an axis or line disposed transversely to elongate portion **441** and longitudinal axis **303** and preferably disposed perpendicularly to the elongate portion **441** an the longitudinal axis **303**.

Each of flanges **442** is sized and shaped so as to be substantially rigid and thus not bend relative to elongate portion **441** during pivoting of mirror **220** about longitudinal axis **303**. Each of the substantially rigid flanges **442** preferably has the shape of a parallelepiped and, more specifically, has a half length measured sidewise of the elongate portion **441** ranging from 20 to 100 microns, a width measured parallel to axis **303** ranging from 4 to 8 microns and a depth measured from the upper surface of plate layer **342** extending downwardly ranging from 4 to 10 microns. Flange **442** is preferably spaced apart from mirror platform **341** a distance ranging from 4 to 12 microns or more preferably a distance of approximately 5 microns. The portion of elongate portion **441** between flange **442** and frame **346** can have a cross-sectional size and shape different than the cross-sectional size and shape of the portion of the elongate portion **441** between flange **442** and mirror platform **341**. Each of tethers **431** and **432** has a length measured perpendicularly to longitudinal axis **303** ranging from 40 to 100 microns, a width generally corresponding to or narrower than the width of flange 442 and a depth ranging from 0.2 to 1.0 microns. The tethers have a cross-sectional shape so that as to be elastic and bendable along at least a portion of their length and preferably along their entire length.

Although first and second tethers **431** and **432** of suspension **429** are shown as being coupled to each of the first and second torsional hinges **306** and **307**, it should be appreciated that a suspension **429** having a single set of tethers **431** and **432** coupled to only one of the hinges **306** or **307** can be provided. Alternatively, first and second tethers can be provided, one tether being coupled to first hinge **306** and the other tether being coupled to second hinge **307** and extending parallel to the first tether in an opposite direction relative to longitudinal axis **303**. Other configurations of tethers can alternatively be provided for regulating or limiting the pivotal movement of mirror **220** about longitudinal axis **303**. It should be further appreciated that one or more tethers can be provided which are joined integral to or otherwise secured directly to the elongate portion **441** of the hinge **306** or **307**, that is without flange **442**, and be within the scope of the present invention. Other arrangements for suspending mirror 220 with flexural members, such as tethers, that provide for a nonlinear restoring torque with or without the presence of torsional hinges, including with tethers that are not necessarily deployed perpendicularly to the mirror's longitudinal axis, are within the scope of this invention. For example, one or more tether-like members can be provided for pivotally securing mirror **220** to frame **346** and for providing a nonlinear restoring torque to the mirror. In one embodiment of such a configuration, four of such flexural or tether members can be provided, the tethers being symmetrically disposed relative to axis **303** and each such tether extending at a 45° or other oblique angle relative to axis **303**.

The following equations were derived to better understand the relationship between the actuation voltage of first and second drive electrodes **322** and **323** as function of the deflection angle of mirror **220** about longitudinal axis **303** so as to provide a mirror assembly **200** having a suspension with a nonlinear force component. The relationship between the rotation angle θ of suspension 429 and the applied torque T_s at the extreme side of mirror **220** was assumed to take on the following form:

$$T_s = k_1\theta + k_3\theta^3 \tag{1}$$

where k_1 is the linear rotational spring constant for the suspension 42) and k_3 is the cubic spring constant for the suspension 429. θ is given in units of radians where, for example, 2 degrees equals approximately 0.035 radians. In establishing an angular deflection of mirror **220**, T_s is in equilibrium with the electrostatic torque T_e generated by applying a voltage V to either one of drive electrodes **322** and **323**. Assuming that mirror **220** is relatively rigid, the angular deflection of the mirror is equivalent to θ in equation (1). The electrostatic torque is represented by the equation:

$$T_e = \frac{V^2}{2}\frac{\partial C}{\partial \theta} \tag{2}$$

where C is the capacitance between mirror **220** and drive electrodes **322** and **323**. The capacitance for such a structure is typically a nonlinear function of the initial air gap g between the electrodes, the drive electrode width b/2, the drive electrode length a, the deflection angle, the specific geometry of mirror **220**, and the permittivity of free space ϵ_0. When the geometry of mirror **220** is relatively complex, finite element methods may be used to determine the capacitance as a function of deflection angle for any given geometry of the mirror. However, for the simple case of a flat rectangular mirror plate platform **341** having a length equal to that of the drive electrodes **322** and **323** and a half-width equal to the width of the drive electrodes, a closed form relationship for the capacitance is obtainable. For such a device that is assumed to undergo only rotational movement, that is no translation of the mirror plate **220** as the result of the applied voltage from electrodes **322** and **323**, the capacitance is represents by the equation:

$$C = -\frac{\varepsilon_0 a}{\theta}\ln\left(1 - \frac{b\theta}{2g}\right). \tag{3}$$

The capacitance for mirror **220** has been analyzed through finite element methods to be capable of being curve-fit to the equation:

$$C = -A\frac{\varepsilon_0 a}{\theta}\ln\left(1 - B\frac{b\theta}{2g}\right). \tag{4}$$

where A and B are fitting parameters that are dependent on the specific rib **411** and mirror platform **341** geometry for a given design of the mirror **220**. For a standard cross-ribbed mirror of the type shown in FIG. **10** of copending U.S. patent application Ser. No. 09/192,006 filed Nov. 13, 1998 [File

No. A-66166-1] and described therein, A and B were found to be equal to 0.8525 and 1.311, respectively.

In determining the relationship between the actuation voltage V and the angular deflection θ of mirror **220**, equations (3) and (4) can be used to evaluate the electrostatic torque T_e of equation (2). The relationship $T_e=2T_s$, where the factor 2 accounts for the presence of a suspension **429** at each end of mirror platform **341**, can then be used to relate equation (2) to equation (1). Solving for the actuation voltage V, the following equation is derived:

$$V = \sqrt{\frac{4\theta^3(k_1 + k_3\theta^2)}{\varepsilon_0 aA\left[\ln\left(1 - B\frac{b\theta}{2g}\right) + \frac{B\frac{b\theta}{2g}}{1 - B\frac{b\theta}{2g}}\right]}} \tag{5}$$

With respect to equation (5), the design issue for the suspension **429** provided by each torsional hinge **306** and **307** and respective tether **431** and **432** is to et the relative magnitudes of k_1 and k_3 to provide the most useful functional relationship between angular deflection and actuation voltage. Another design constraint for mirror **220** is its resonant frequency f_{res} represented by the equation:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k}{I_m}} \tag{6}$$

where k is the effective spring constant for the torsional mode and I_m is the mass moment of inertia of the mirror **220**. Due to the inherent nonlinearity of suspension **429**, this resonant frequency will be a function of the deflection angle θ. However, for the servo loop control employed for the mirror angular position, it is sufficient to design the resonant frequency assuming that $k=2k_2$ where, again, the factor of 2 accounts for the presence of two suspensions **429**, one each at either end of mirror platform **341**. Finite element analysis for the polysilicon cross-ribbed mirror has determined that I_m=5.36E−13 kg mm^2. For a torsional resonance design value of 30-kHz, k_1 is then determined to be 0.0095 mN mm (milinewton millimeter).

If it is assumed that pull-in for mirror **220** occurs at a deflection angle of approximately 1.5 degrees, one approach for the design of the suspension **429** formed by hinges **306** and **307** and tethers **431** and **432** is to ensure that the cubic term of equation (1) becomes significant at a deflection angle of 1.5 degrees so as to prevent pull-in. Taking the cubic term to be 20% of the linear term at this angle dictates that k_3 ought to be on the order of 290 times k_1. Given the value for k_1 derived in the preceding paragraph, k_3 is then calculated to be 2.77 mN mm. In this design, referred to as Design 1 herein, the initial gap between the drive electrodes **322** and **323** and the lower surface of platform **341** is assumed to be approximately 10 microns. Equation (5) has been evaluated for the cross-ribbed mirror **220** having the values of k_1 and k_3 referred to above, a=200 μm and b=140 μm, the resulting relationship being plotted in FIG. **11**. Plotted on the same axes in FIG. **11** is the same relationship but with k_3=0, which represents the performance of the suspension **429** without tethers **431** and **432**. As can be seen from FIG. **11**, pull-in becomes a problem as the slope of the curve where k_3=0 tends towards zero. It is apparent from FIG. **11** that the tethered suspension **429** gives better immunity from pull-in out to a deflection angle of at least 2 degrees.

Design **1** gives a nearly quadratic relationship between angular deflection and actuation voltage. This is a useful approach given that a servo loop control in an optical data storage system can use a quadratic relationship to update the angular position of the mirror to correct for off-track positional error during track following. In FIG. **12**, the same voltage data of FIG. **11** is squared and plotted versus the deflection angle θ. Note that the untethered mirror shows significant departure from linearity starting at about 1 degree of deflection, whereas the tethered mirror remains fairly linear as is evidenced from comparison of it to its least squares regression line.

In another design, referred to herein as Design 2, the relationship between the actuation voltage V and the angular deflection θ is made to be as linear as possible. For this design, we make the assumption that the mirror resonant frequency can be reduced somewhat without adversely affecting the servo loop control for the mirror position. Design 2 is further attractive in that the initial gap between the lower surface of mirror platform **341** and the first and second drive electrodes **322** and **323** is reduced below 10 μm. This design consideration serves to lower the necessary actuation voltage V for the pivoting of mirror **220** about longitudinal axis **303**. Allowing for a somewhat lower resonant frequency allows k_1 to be reduced to, for example, 0.0080 mN mm. Setting k_3 to be 2500 times k_1, that is 20.0 mN mm and reducing the initial air gap to approximately 7 μm provides the approximate desired linear relationship out to at least 2 degrees of deflection as shown in FIG. **13**. The dotted line in FIG. **13** represents the slope of equation (5) evaluated for one degree of deflection. For this calculation, the coefficients A and B of equation (5) are assumed to be the same as for the 10 μm initial gap case of Design 1.

To determine the geometry that gives the k_1 and k_3 values for Designs 1 and 2, nonlinear finite element analysis was performed using SDRC I-deas Master Series 6 software. The geometrical parameters that can be varied to give the desired values are shown in FIG. **14**. The table of FIG. **15** gives the k_1 and k_3 results of this analysis and the required geometry for Designs 1 and 2. Dimensions are in microns, and the spring constants are in mN mm. A Young's modulus of 160 GPa and a Poisson's ratio of 0.3 were assumed, which are typical values for the polysilicon plate layer **342** used to construct the suspensions. FIG. **15** shows that the geometries listed are within reasonable agreement with the design goals specified in the previous discussion.

FIG. **16** shows plots of the angular deflection of the tethered suspension designs as a function of the applied electrostatic moments provided by first and second drive electrodes **322** and **323**. Results from the nonlinear finite element analysis have been plotted along with the polynomial curve fits that include only linear and cubic terms having the k_1 and k_3 coefficients listed above. The fact that the curve fitting matches the finite element analysis results nearly exactly indicates that the supposition that the tethers behave as equation (1) is, in fact, correct.

The method for manufacturing mirror assembly **200** is described in detail in copending U.S. patent application Ser. No. 09/192,006 filed Nov. 13, 1998 [File No. A-66166-1]. As more fully described therein, elongate portions **441** of first and second torsional hinges **306** and **307** are formed from plate layer **342**. First and second tethers **431** and **432** can also be formed from plate layer **342**. The desired depth or thickness of tethers **431** and **432** can be obtained by thinning away the upper portion of the plate layer **342**, by means of etching or otherwise, at the desired locations of the tethers. Alteratively, the plate layer **342** can be etched

completely away at the locations of tethers **431** and **432** and an additional layer of any suitable material, such as the polysilicon material of plate layer **342**, deposited, patterned and etched to form the tethers. Such an approach would likely enhance the control of the tether thickness. In yet a further alternative, tethers **431** and **432** could be constructed from an additional layer of silicon nitride or low stress silicon-rich silicon nitride that is appropriately deposited, patterned and etched to create the tethers. The portions of flanges **442** in the plane of plate layer **342** are formed in the same manner as elongate portions **441**, while the portion of flanges **442** depending below the plate layer **342** can be formed in the same manner as ribs **411**. In embodiments of mirror assembly **200** such as Design 2 where the relatively small gap between ribs **411** and planar base **301** results in the ribs **411** undesirably contacting planar base **301**, trenches (not shown) of appropriate depth and size can be etched or otherwise formed in the planar base to accommodate ribs **411** during movement of mirror **220** about longitudinal axis **303**.

Each of the mirror assemblies **200** is attached to a flying head **100** by adhering slider attach area **200***b* of the mirror assembly to angled face **202** of slider body **444**. As shown most clearly in FIG. **2**, where the bottom surface of substrate **311** is visible, the mirror assembly **200** is aligned on slider body **444** such that mirror **220** reflects laser beams **191,192** between extremity **102***b* of optical fiber **102** and objective objects **446**. In the embodiment illustrated, mirror **220** reflects the laser beams through an angle of approximately 90° relative to the axis defined by the propagation direction of the impinging beam. It is preferable that laser beams **191**, **192** each contact mirror **220** at the center thereof. Each mirror assembly **200** can be tested before and/or after its attachment to a flying head **106**. Contact pads **391**–**393** are electrically coupled to controller **112** by means of respective wires as shown in FIG. **2**.

In operation and use of system **100**, control voltages are applied by the outputs of servo controller **112** to one of first and second drive electrodes **322** and **323** to cause mirror **220** to pivot about hinges **306** and **307** in first or second opposite directions between its first and second deflected positions. The drive voltages are supplied to first and second electrodes **322** and **323** by means of first and second contact pads **391** and **392**. Maximum drive voltages range from 100 to 200 volts, preferably from 120 to 150 volts and more preferably approximately 135 volts. The electrostatic force between the drive electrode **322** or **323** and the respective mirror half **220***c* or **220***d*, grounded by means of ground contact pad **393**, cause the mirror **220** to pivot about rotational axis **303**.

The mirror **220** pivots from its home position, in either direction about mirror axis **303**, through a deflection angle ranging from 0 to 2.5° and preferably approximately 2° when traveling from its home position to its fully deflected position. The controller **112** provides drive signals to first and second drive electrodes **322** and **323** at the Nyquist rate of approximately 19 kHz. The mirror **220** has a resonant frequency ranging from 25 to 50 kHz and preferably ranging from 25 to 30 kHz. Mirror assembly **200** reflects laser beams **191,192** between the distal extremity **102***b* of optical fiber **102** and the storage surface **109** of disk **107** to permit the optical recording and/or reading of information on the data tracks **110** of the storage surface **109**.

Mirror **220** is restrained during such rotation by the restoring torque of suspension **429**. As discussed above, suspension **429** includes a linear component such as elongate portions **441** of first and second torsional hinges **306** and **307** and a nonlinear component that includes flanges **442** and first and second tethers **431** and **432**. As shown in FIG. **7**, tethers **431** and **432** and related flanges **442** are disposed in the plane of plate layer **342** when mirror **220** is in its undeflected position. When the mirror **220** is pivoted about axis **303**, tethers **431** and **432** bend and elongate to restrain the mirror **220** from pivoting beyond a predetermined angle (see FIG. **18**). The substantially rigid flanges **442** do not bend or stretch during movement of the mirror. However, the attachment of inner ends **434** of the tethers to first and second ends **442***a* and **442***b* of the flanges **442** enhance bending and stretching of tethers **431** and **432**. More specifically, the moment arm resulting from the spacing of ends **442***a* and **442***a* at positions spaced apart from pivot axis **303** causes greater elevational movement and bending movement of the tethers **431** and **432** than if the tethers were secured directly to elongate portions **441** of the hinges **306** and **307**.

The tethers **431** and **432** are designed such that for small angular deflections they provide a linear restoring torque that adds to but is smaller than the restoring torque provided by hinges **306** and **307**. This linear restoring torque is provided by the bending of the tethers. As the angular deflection of mirror **220** is increased, the tethers are forced to stretch to accommodate the angular deflection. The stretching of the tethers is nonlinear, and more specifically a cubic function of the deflection angle of mirror, and can therefore be use to balance the nonlinear nature of the electrostatics of mirror assembly **200**. In this manner suspension **429** with its nonlinear component permits the stable angular deflection range of mirror **220** to be increased by increasing the pull-in angle of the mirror. The attachment of tether **431** and **432** to torsional hinges **306** and **307** serves to inhibit undesirable bending of mirror **220** from the force of the tethers during pivotal movement of the mirror about longitudinal axis **303**.

Fine tracking and short seeks to a series of nearby tracks **110** may be performed by rotating the mirror **220** about rotational axis **303** so that the propagation angle of the outgoing laser beam **191** is changed before transmission to the objective optics **246**. Mirror **220** thus enables the focused optical spot **248** to be moved in the radial direction of the MO disk **107** for storage and/or retrieval of information, track following, and seeks from one data track **110** to another data track. Coarse tracking may be maintained by adjusting a current to the rotary actuator magnet and coil assembly **120** (see FIG. **4**). The track following signals used to follow a particular track **110** of the MO disk **107** may be derived using combined coarse and fine tracking servo techniques that are well known in the art. For example, a sampled sector servo format may be used to define tracks. The servo format may include either embossed pits stamped into the MO disk **107** or magnetic domain orientations that are read similar to data marks.

Irrespective of the movement of the set of actuator arms **105**, a set of the mirror assemblies **200** of the present invention may be used to operate independently and thus permit track following and seeks so as to read and/or write information using more than one MO disk surface **109** at any given time. Independent track following and seeks using a set of concurrently operating mirror assemblies **200** preferably require a set of separate respective read channel and fine track electronics and mirror driving electronics. The small size and mass of the mirror assembly **200** contributes to the ability to design the flying head **106** with a low mass and a low profile.

The optical light emitter and receiver described herein can include a laser source carried by the read and/or write head

in close proximity to the mirror assembly. In one such embodiment, the optical light emitter and receiver includes a laser source and one or more suitable polarization sensitive detectors. Such a system may or may not need a fiber optical element to transmit laser beams to or from the mirror assembly.

The mirror assemblies described above can be used in other than a flying magneto-optical head. For example, mirror assembly **220** can be utilized in any suitable optical recording and/or reading system. One application is in retrieving optical information from media using physical recording methods (e.g., CD-ROMs having data recorded as physical pits or depressions for reflecting and modulating the phase or intensity of a beam of incident light). The micromachined mirror assembly of the present invention may also have application in retrieving optical data from media having data storage locations providing optical phase modulation in the absence of magnetic fields. In addition, the micromachined mirror assemblies disclosed herein can be used outside of data recording and/or retrieval systems in applications that require a small deflectable mirror. For example, mirror assemblies **220** can be utilized in bar code scanning or optical switching in telecommunications or other areas. Mirror assemblies **220** with less than two drive electrodes or without drive electrodes, such as for use as sensors, are also contemplated hereby.

While the foregoing detailed description has described embodiments of the micromachined mirror assembly in accordance with this invention, it is to be understood that the above description is illustrative only and not limiting of the disclosed invention. It will be appreciated that it would be possible to modify the size, shape and appearance and methods of manufacture of various elements of the invention or to include or exclude various elements within the scope and spirit of this invention. In this regard, it should be appreciate that the utilization of any suspension for mirror **220** that includes a restoring torque component that is a nonlinear function of the deflection angle of the mirror, whether such component is coupled to one or more torsional hinges, the mirror itself or any combination thereof, is within the scope of the present invention.

From the foregoing, it can be seen that an improved micromachined mirror assembly having a restoring torque that increases nonlinearly with the deflection angle of the mirror to substantially compensate for the nonlinear electrostatic drive forces of the mirror assembly has been provided. Such a mirror assembly increases the pull-in angle so as to increase the useful deflection range of the mirror. In one embodiment, the mirror assembly is provided with one or more tethers coupled to the torsional hinges secured to the mirror. The tethers stretch during pivotal movement of the mirror to provide a nonlinear restoring torque to the mirror. The torsional hinges are preferably provided with substantially rigid flanges to which the tethers are joined. The flanges serve to enhance stretching of the tethers.

What is claimed is:

1. A mirror assembly of micron dimensions for use in deflecting a beam of light comprising a planar base, a planar mirror spaced apart from the planar base and disposed generally parallel to the planar base, the planar mirror having first and second end portions and a longitudinal axis extending between the first and second end portions, first and second torsional members extending along the longitudinal axis and connected to the respective first and second end portions for permitting the mirror to rock between first and second positions about the longitudinal axis relative to the planar base, means for securing the first and second torsional members to the planar base, at least a portion of the mirror being of a conductive material, first and second spaced-apart electrodes carried by the planar base for driving the mirror between the first and second positions, a tether member extending transversely of the longitudinal axis and being secured to the first torsional member and means for securing the tether member to the planar base whereby the tether member regulates the rocking of the mirror.

2. The mirror assembly of claim **1** wherein the means for securing the first and second torsional members to the planar base and the means for securing the tether member to the planar base includes a frame member extending around the mirror, the first and second torsional members and the tether member being secured to the frame member and the frame member being spaced apart from and secured to the planar base.

3. The mirror assembly of claim **1** wherein the tether member has a length and at least a portion of the tether member is elastic along the length and wherein the first torsional member includes an elongate portion extending along the longitudinal axis and a substantially rigid flange portion extending transversely of the elongate portion and having an end spaced outwardly from the elongate portion, the tether member being secured to the end of the flange portion whereby the flange portion enhances stretching of the tether member during rocking of the mirror between the first and second positions.

4. A mirror assembly of micron dimensions for use in deflecting a beam of light comprising a planar base, a planar mirror spaced apart from the planar base and disposed generally parallel to the planar base, the planar mirror having first and second end portions and a longitudinal axis extending between the first and second end portions, first and second torsional members extending along the longitudinal axis and connected to the respective first and second end portions for permitting the mirror to rock between first and second positions about the longitudinal axis relative to the planar base, means for securing the first and second torsional members to the planar base, at least a portion of the mirror being of a conductive material, first and second spaced-apart electrodes carried by the planar base for driving the mirror between the first and second positions, first and second tether members extending transversely of the longitudinal axis and being secured to at least one of the first and second torsional members and means for securing the first and second tether members to the planar base whereby the first and second tether members regulate the rocking of the mirror.

5. The mirror assembly of claim **4** wherein each of the first and second tether members has a length and wherein at least a portion of each of the first and second tether members is elastic along the length.

6. The mirror assembly of claim **4** wherein the at least one of the first and second torsional members includes an elongate portion extending along the longitudinal axis and a substantially rigid flange portion extending transversely of the elongate portion and having a first end spaced outwardly from the elongate portion, the first tether member being secured to the first end of the flange portion whereby the flange portion enhances stretching of the first tether member during rocking of the mirror between the first and second positions.

7. The mirror assembly of claim **6** wherein the flange portion has a second end spaced outwardly from the elongate portion opposite of the first end, the second tether member being secured to the second end of the flange portion.

8. The mirror assembly of claim 6 wherein the flange portion extends perpendicularly of the elongate portion.

9. The mirror assembly of claim 4 wherein the at least one of the first and second torsional members includes an elongate portion extending along the longitudinal axis and a substantially rigid flange portion extending perpendicularly of the elongate portion and having first and second opposite ends spaced outwardly from the elongate portion, the first tether member being secured to the first end of the flange portion and the second tether member being secured to the second end of the flange portion whereby the flange portion enhances stretching of the first and second tether members during rocking of the mirror between the first and second positions.

10. The mirror assembly of claim 4 wherein the first and second tether members are secured to the first torsional member.

11. The mirror assembly of claim 10 wherein the first and second tether members extend along an axis extending transversely of the longitudinal axis.

12. The mirror assembly of claim 11 wherein the first and second tether members extend along an axis extending perpendicularly of the longitudinal axis.

13. The mirror assembly of claim 10 further comprising an additional set of first and second tether members, the additional set of first and second tether members being secured to the second torsional member.

14. A mirror assembly of micron dimensions for use in deflecting a beam of light comprising a planar base, a planar mirror spaced apart from the planar base and disposed generally parallel to the planar base, the planar mirror having first and second end portions and a longitudinal axis extending between the first and second end portions, at least a portion of the mirror being of a conductive material, at least one stretchable member extending transversely of the longitudinal axis and being secured to the mirror and means for securing the stretchable member to the planar base whereby the mirror is rockable between first and second positions about the longitudinal axis and the stretchable member provides a nonlinear restoring force to the mirror during rocking of the mirror.

15. The mirror assembly of claim 14 further comprising a least one electrode carried by the planar base for rocking the mirror about the longitudinal axis.

16. The mirror assembly of claim 14 further comprising first and second torsional members extending along the longitudinal axis and connected to the respective first and second end portions and means for securing the first and second torsional members to the planar base.

17. The mirror assembly of claim 16 wherein the stretchable member is secured to the mirror by means of one of the torsional members.

18. An optical data storage system comprising a support body, an optical disk rotatably mounted on the support body and having a planar storage surface, the storage surface having a plurality of concentrically disposed data tracks, an arm having proximal and distal extremities, the proximal extremity of the arm pivotably mounted on the support body so that the distal extremity of the arm can pivot between first and second positions relative to the storage surface, a flying optical head mounted on the distal extremity of the arm for aerodynamic suspension adjacent the storage surface during rotation of the disk on the support body, an optical light emitter and receiver emitting a laser beam carried by the arm and a mirror assembly of micron dimensions carried by the head for reflecting the laser beam between the optical light emitter and receiver and the storage surface of the disk to permit the optical recording and/or reading of information on the data tracks of the storage surface, the mirror assembly having a planar base and a planar mirror spaced apart from the planar base and disposed generally parallel to the planar base, the planar mirror having first and second end portions and a longitudinal axis extending between the first and second end portions, the mirror assembly including first and second torsional members extending along the longitudinal axis and connected to the first and second end portions and means for securing the first and second torsional members to the planar base whereby the mirror is rockable between first and second positions about the longitudinal axis relative to the planar base, at least a portion of the mirror being of a conductive material, the mirror assembly having first and second spaced-apart electrodes carried by the planar base for driving the mirror between the first and second positions, the mirror assembly being provided with first and second tether members extending transversely of the longitudinal axis and being secured to at least one of the first and second torsional members and means for securing the first and second tether members to the planar base whereby the first and second tether members regulate the rocking of the mirror.

19. The data storage system of claim 18 wherein the first torsional member includes an elongate portion extending along the longitudinal axis and a substantially rigid flange portion extending perpendicularly of the elongate portion and having first and second opposite ends spaced outwardly from the elongate portion, the first tether member being secured to the first end of the flange portion and the second tether member being secured to the second end of the flange portion whereby the flange portion enhances stretching of the first and second tether members during rocking of the mirror between the first and second positions.

20. The data storage system of claim 19 wherein the first and second tether members are secured to the first torsional member, further comprising an additional set of first and second tether members, the additional set of first and second tether members being secured to the second torsional member.

* * * * *

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(12) **United States Patent**
Chin et al.

(10) **Patent No.: US 6,404,534 B1**
(45) **Date of Patent: Jun. 11, 2002**

(54) **MICRO-MIRROR DEVICE AND DRIVING METHOD**

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(73) Assignee: **Samsung Electronics Co., Ltd.**, Kyungki-Do (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/698,138**

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(30) **Foreign Application Priority Data**

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(52) **U.S. Cl.** **359/295**; 359/291; 359/293; 359/224; 359/230; 359/254; 359/846; 348/771; 427/162

(58) **Field of Search** 359/223, 224, 359/230, 254, 290, 291, 292, 293, 295, 298, 846, 847, 848; 427/162, 255.6, 534; 348/771, 571; 347/239

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(74) *Attorney, Agent, or Firm*—Sughrue Mion, PLLC

(57) **ABSTRACT**

A micro-mirror device and associated method, the device including a substrate, address electrodes provided on the substrate, and a micro-mirror facing the substrate and spaced a predetermined distance from the substrate. The micro-mirror device is adapted so that the slope of the micro-mirror can be adjusted by electrostatic attraction forces between the address electrodes and the micro-mirror. The micro-mirror device further includes auxiliary electrodes formed on and projected from the substrate. The upper portions of the auxiliary electrodes are disposed in the vicinity of the micro-mirror, so that distances between the micro-mirror and the auxiliary electrodes can remain small, even when the micro-mirror is inclined by electrostatic attraction forces in one direction. Accordingly, restoration of the micro-mirror is enhanced by electrostatic attraction forces of the auxiliary electrodes.

11 Claims, 6 Drawing Sheets

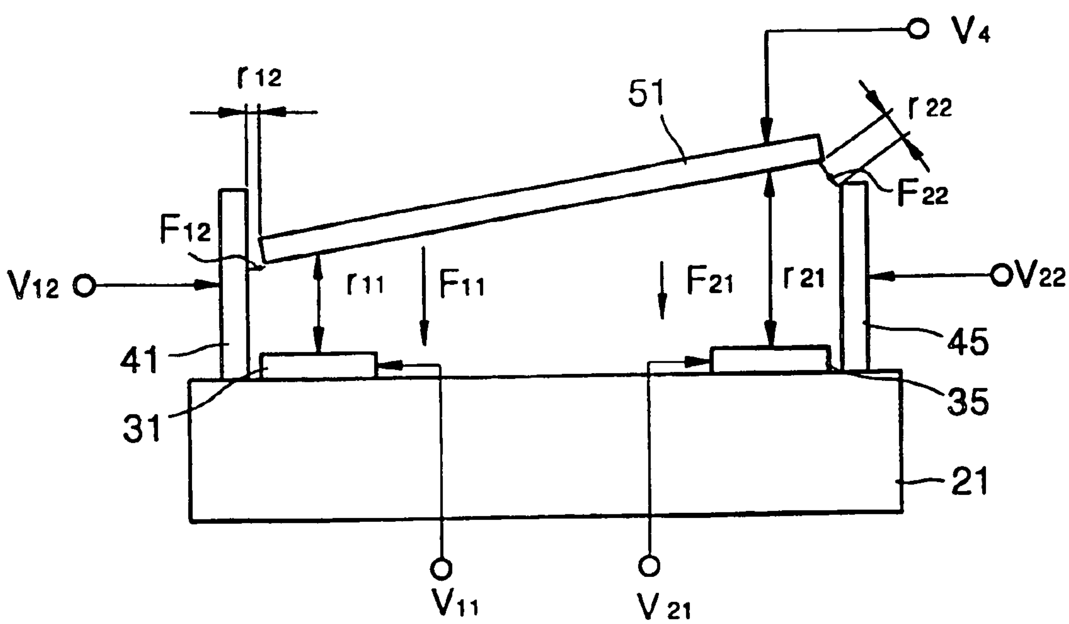


FIG. 1

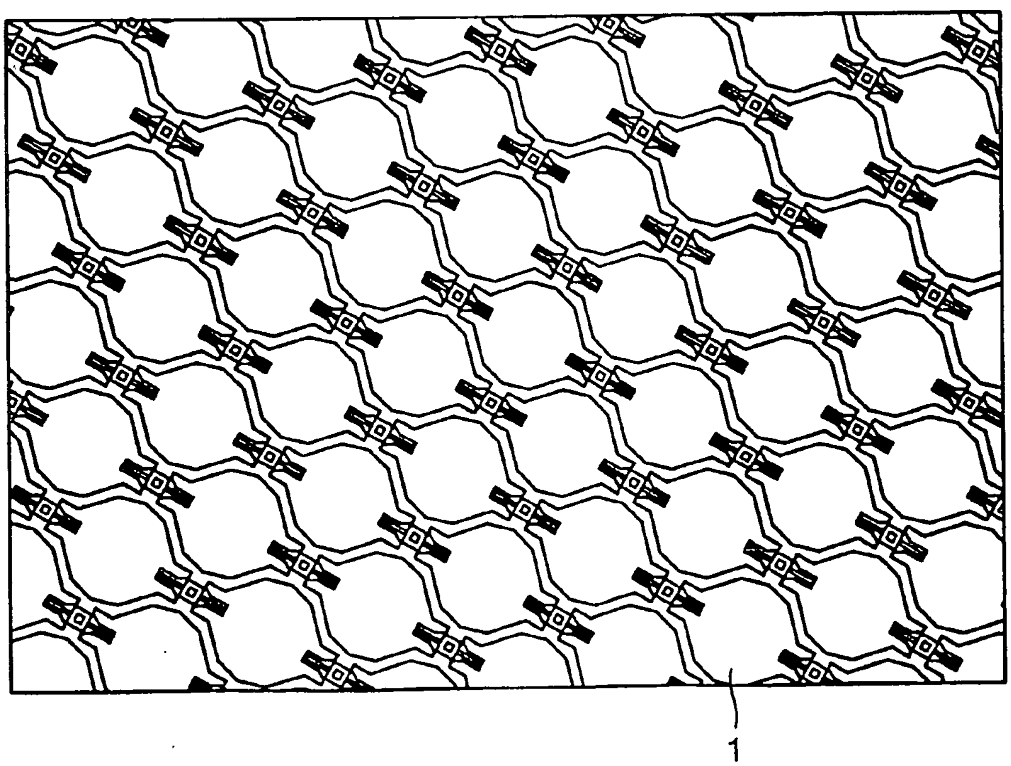


FIG. 2 (PRIOR ART)

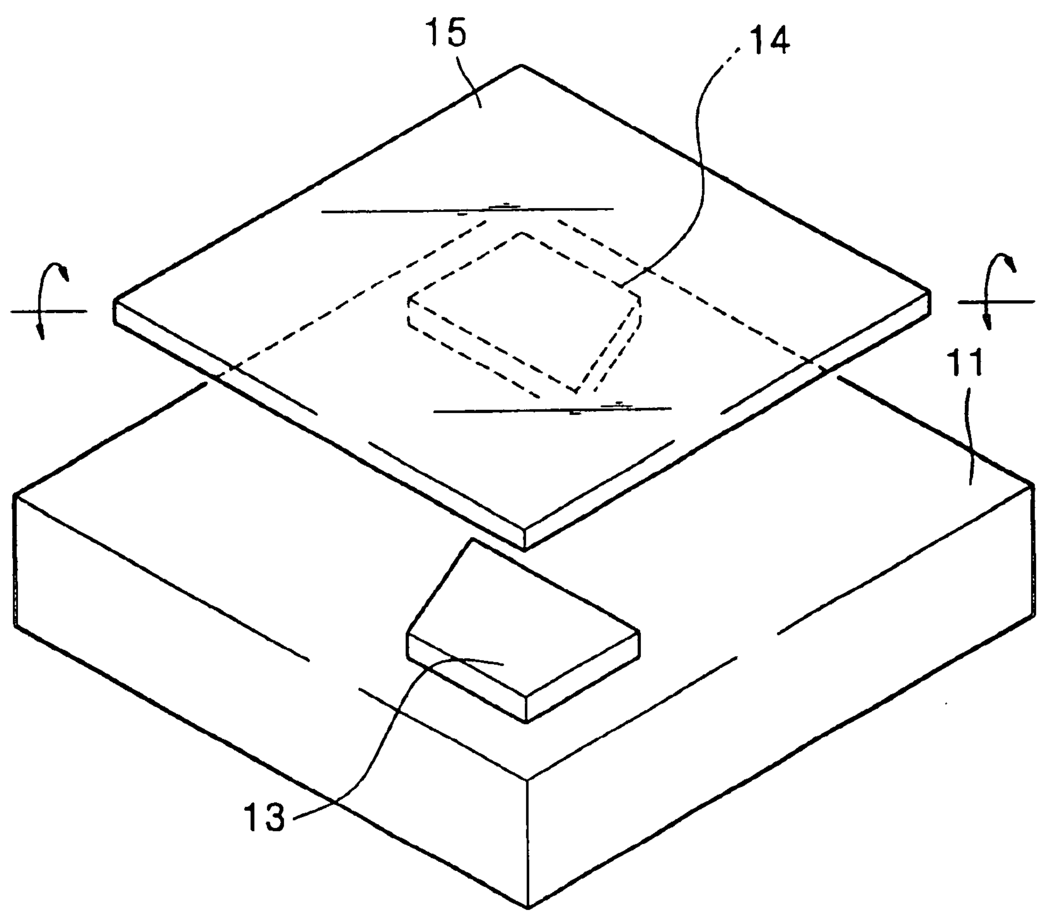


FIG. 3 (PRIOR ART)

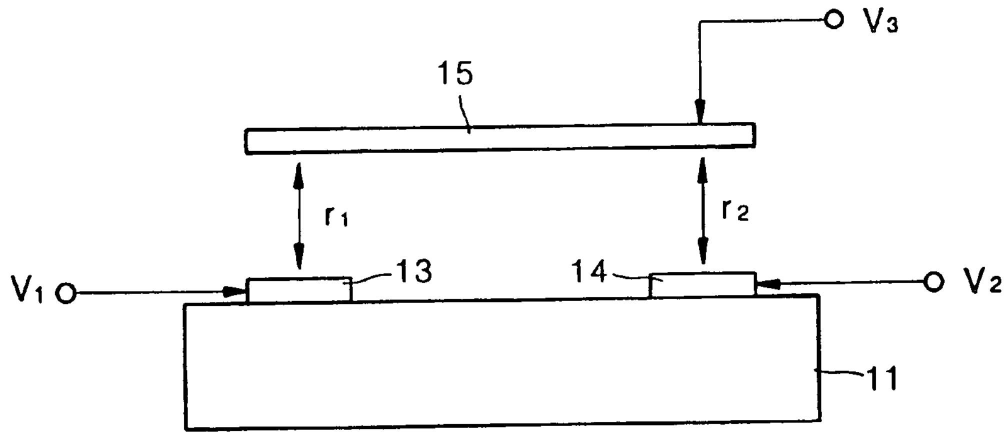


FIG. 4 (PRIOR ART)

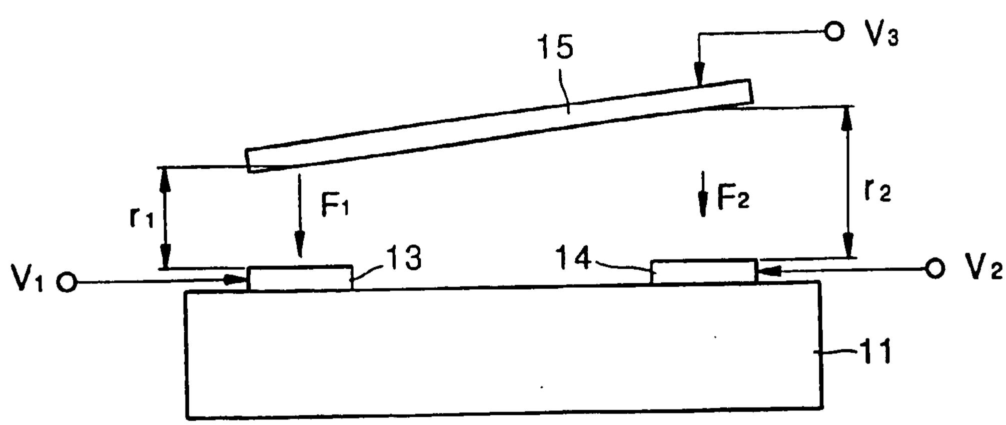


FIG. 5

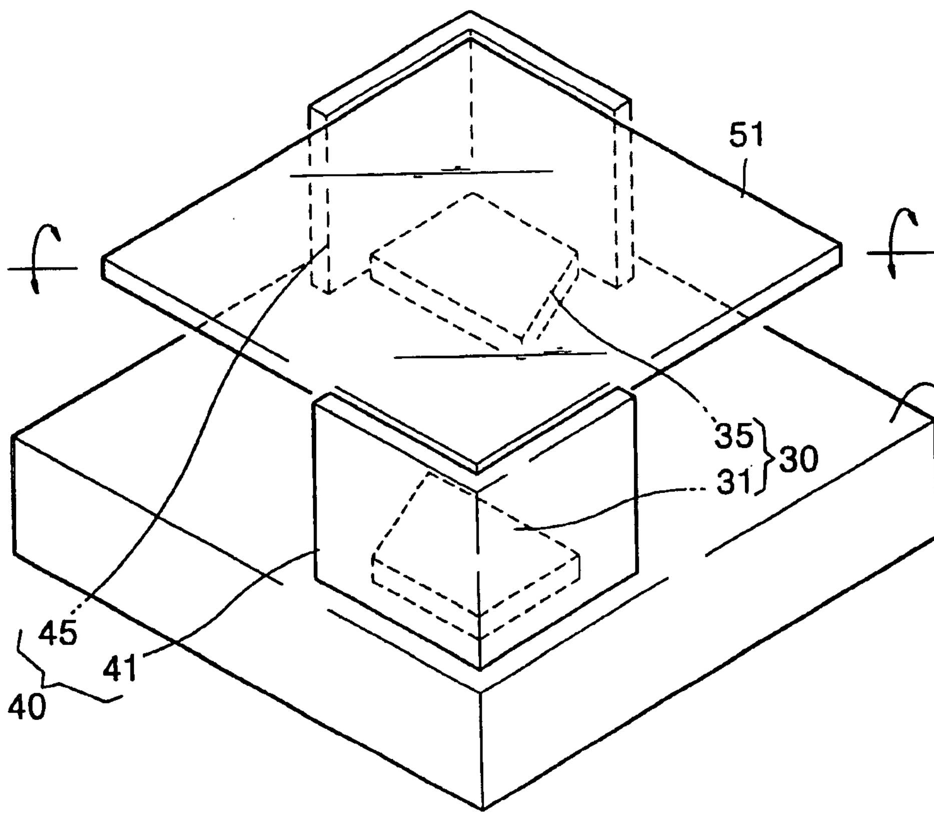
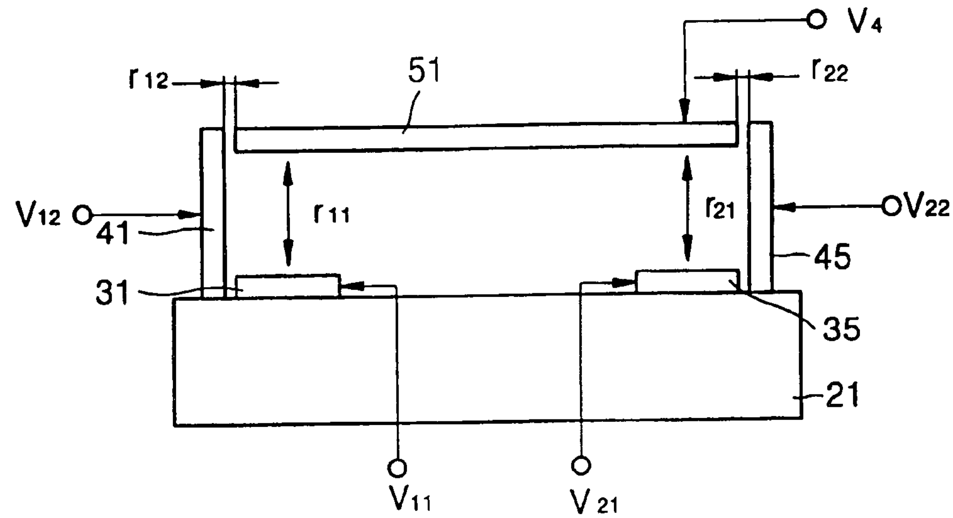


FIG. 6


V4
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r22
V12
41
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r21
V22
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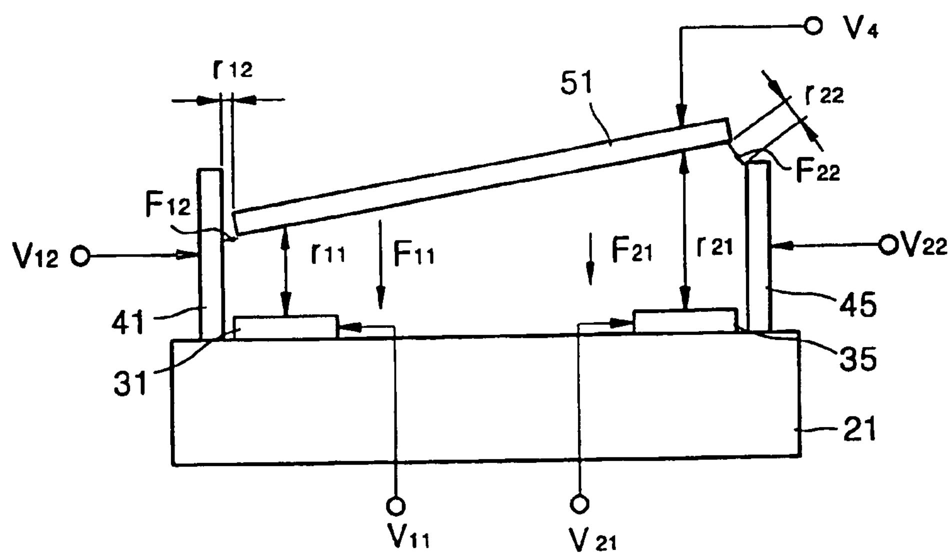
21
V11
V21

FIG. 7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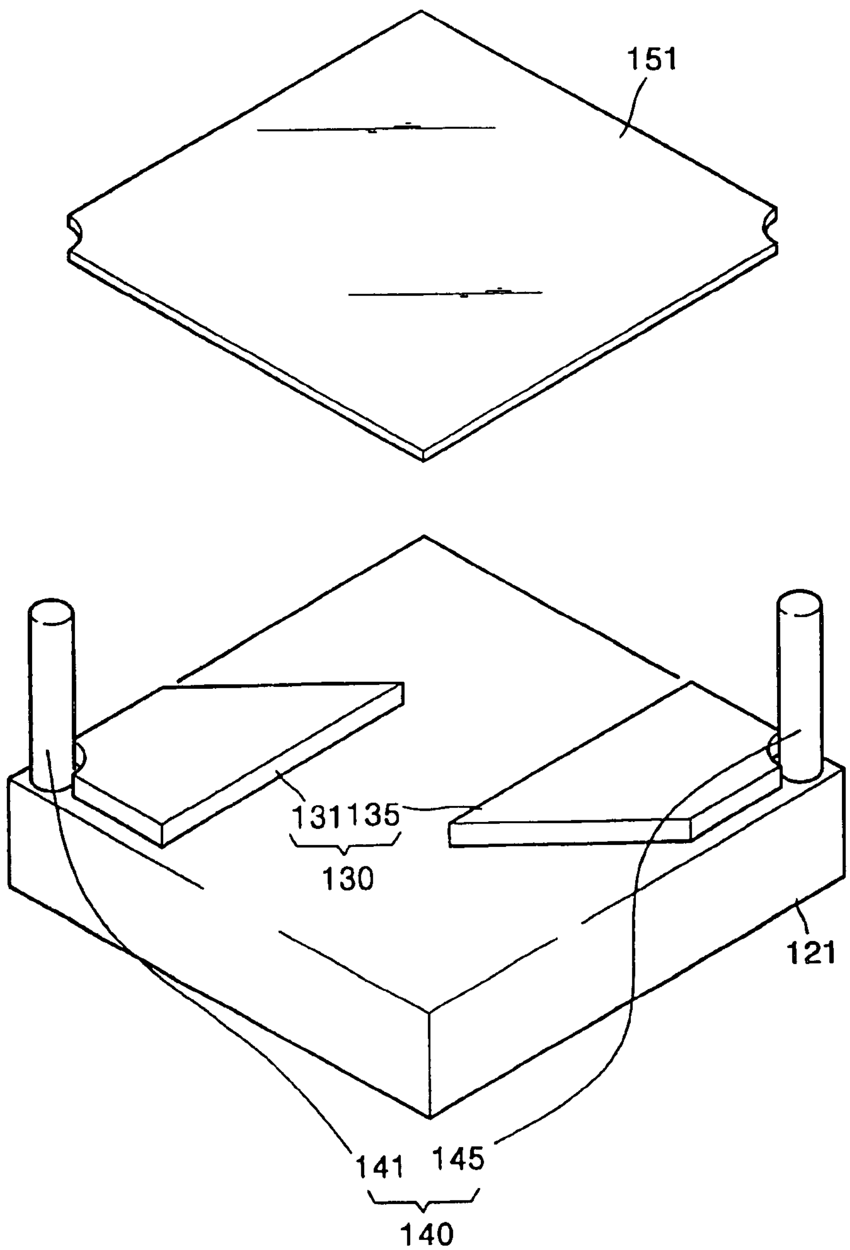
V11
V21

FIG. 8



MICRO-MIRROR DEVICE AND DRIVING METHOD

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a micro-mirror device and an associated method, the device adapted so as to change the reflection path of an incident light beam by pivoting a micro-mirror using electrostatic attraction forces. More particularly, the present invention relates to a micro-mirror device and an associated method, the device having an improved structure for restoring the micro-mirror skewed by electrostatic attraction forces to its original position.

2. Description of the Related Art

A general micro-mirror device array is an array in which a plurality of micro-mirrors are installed so as to be pivoted by electrostatic attraction forces, and to reflect incident light beams at different reflection angles depending on pivoting angles or directions. Applications of micro-mirror device arrays include an image displaying apparatus of a projection television and various laser scanning devices such as a scanner, copier, or facsimile machine. In particular, when a micro-mirror device array is employed in an image displaying apparatus, in the micro-mirror device array, micro-mirrors 1 corresponding to the number of required pixels are arranged in an array in a two-dimensional plane, as shown in FIG. 1. The micro-mirrors 1 arranged in an array, so as to correspond to respective pixels as described above are independently pivoted according to an image signal, decide respective reflection angles of incident light beams, and, therefore, can form an image.

Such micro-mirror devices are disclosed in, for example, U.S. Pat. No. 5,331,454 entitled "LOW RESET VOLTAGE PROCESS FOR DMD" issued Jul. 19, 1994 and assigned to Texas Instruments Incorporated, and U.S. Pat. No. 5,535,047 entitled "ACTIVE YOKE HIDDEN HINGE DIGITAL MICROMIRROR DEVICE" issued Jul. 9, 1996 and assigned to Texas Instruments Incorporated.

Briefly, as shown in FIG. 2, each of the disclosed micro-mirror devices comprises a substrate 11, first and second address electrodes **13** and **14** provided on the substrate 11, and a micro-mirror disposed to be spaced from and facing the first and second address electrodes 13 and 14.

In the disclosed micro-mirror devices, the micro-mirror **15** is installed on the substrate **11** by means of at least one elastically deformable hinge or post so as to be pivotable, and is maintained in a horizontal position by an elastic restoring force. As the structure of such a hinge or post is described in the above-mentioned inventions, a detailed description thereof is omitted.

In the micro-mirror device having the structure as described above, when respective voltages are applied to the first and second address electrodes **13** and **14** and the micro-mirror **15**, the micro-mirror **15** is inclined by electrostatic attraction forces formed according to the differences in electric potentials between the first address electrode **13** and the micro-mirror **15** and between the second address electrode **14** and the micro-mirror **15** to the side having the larger electric potential difference. However, the electrostatic attraction forces must overcome the strength of the hinge or post which tends to keep the micro-mirror in the horizontal position.

That is, as shown in FIG. 3, when voltages V1 and V2 applied to the first and second address electrodes 13 and 14, and voltage V3 applied to the micro-mirror 15 all are zero (0), the micro-mirror **15** is maintained in a horizontal position. Therefore, the distance **r1** between the first electrode 13 and the micro-mirror **15** and the distance **r2** between the second electrode **14** and the micro-mirror **15** are the same.

On the other hand, when voltages **V1, V2,** and **V3** applied to the first and second address electrodes **13** and **14** and the micro-mirror **15**, respectively, have the relationship of $V1<V2<V3$, the electrostatic force **F1** acting between the first address electrode **13** and the micro-mirror **15** is greater than the electrostatic force F2 acting between the second address electrode **14** and the micro-mirror **15**, as shown in FIG. 4. Accordingly, the micro-mirror **15** is pivoted toward the first address electrode **13** side of the substrate **11**, and is inclined to a position where the electrostatic force **F1** is balanced by the sum of the electrostatic force **F2** and a restoring force of the hinge or post, such that the condition of $r1<r2$ is satisfied.

The position of the micro-mirror can also be changed from the position shown in FIG. **4** to the position shown in FIG. 3, or to a position where the micro-mirror is inclined to a direction opposite to the position shown in FIG. **4**. These operations of the micro-mirror device are described as follows.

First, when voltages V1, V2, and V3 which all are zero (0) are applied to the first and second address electrodes **13** and 14, and the micro-mirror 15, the position of the micro-mirror 15 changes to the position shown in FIG. **3** under the restoring force of the hinge or post which tends to maintain the micro-mirror in a horizontal position. In this case, since the dimensions of the hinge or post are on the order of □m, the strength of the hinge is relatively weak with respect to torque, and the restoring force of the hinge is very weak. Therefore, the time required to change the position of the micro-mirror is longer than the desired time for driving the micro-mirror device, creating a problem in that the micro-mirror device cannot be driven at high speed.

Next, when voltages V1, V2, and V3 which have the relationship of $V2<V1<V3$ are applied to the first and second address electrodes **13** and **14** and the micro-mirror **15**, respectively, and the micro-mirror **15** is driven to be inclined in the opposite direction, the position of the micro-mirror 15 is changed by the restoring force of the hinge or post and electrostatic forces. In this case, when electrostatic forces F1 and F2 are compared to each other, the fact that the difference between voltages V2 and V3 exceeds the difference between voltages V2 and V3 does not always mean that the electrostatic force **F2** is greater than the electrostatic force F1. The reason is that the electrostatic forces **F1** and **F2** are inversely proportional to respective squares of distances r1 and r2 between the first and second address electrodes **13** and 14 and the micro-mirror **15**. Therefore, in this case, until distances r1 and r2 become similar to each other due to the restoring force of the hinge, the effect of reducing the time required to change the position of the micro-mirror **15** by applying voltages having reversed values is insignificant.

Therefore, the micro-mirror device having the structure as described above requires a relatively long time to change the position of a micro-mirror by forming electrostatic attraction forces. Consequently, the driving speed of the micro-mirrors is limited.

SUMMARY OF THE INVENTION

To solve the above problem, it is an objective of the present invention to provide a micro-mirror device and an associated method, the device having improved electrode

structures, so that the time required to change the position of a micro-mirror, for example, to change from an inclined position of the micro-mirror to an initial position of the micro-mirror, or to an oppositely inclined position of the micro-mirror, can be reduced.

Accordingly, to achieve the above objective, the present invention provides a micro-mirror device including a substrate, address electrodes being provided on the substrate, and a micro-mirror facing the substrate and spaced a predetermined distance from the substrate. The micro-mirror is adapted so that the slope of the micro-mirror can be adjusted by electrostatic attraction forces between the address electrodes and the micro-mirror. The micro-mirror device includes auxiliary electrodes that are formed on and projected from the substrate and the upper portions of which are disposed in the vicinity of the micro-mirror so that restoring force and restoring speed can be enhanced by electrostatic forces of the auxiliary electrodes when an inclined micro-mirror is restored.

BRIEF DESCRIPTION OF THE DRAWINGS

The above objective and advantage of the present invention will become more apparent by describing in detail preferred embodiments thereof with reference to the attached drawings, in which:

FIG. 1 is a schematic plan view illustrating a conventional micro-mirror device array for an image displaying apparatus;

FIG. 2 is a schematic perspective view illustrating a conventional micro-mirror device;

FIGS. 3 and 4 are schematic side views for describing the operation of the conventional micro-mirror device;

FIG. 5 is a schematic perspective view illustrating a micro-mirror device of an image displaying apparatus according to an embodiment of the present invention;

FIGS. 6 and 7 are schematic side views for describing the operation of the micro-mirror device shown in FIG. 5; and

FIG. 8 is an exploded perspective view illustrating a micro-mirror device of an image displaying apparatus according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 5, a micro-mirror device according to an embodiment of the present invention comprises a substrate 21, electrodes provided on the substrate 21, and a micro-mirror 51 disposed to be spaced from and facing the electrodes. The micro-mirror 51 is installed to be pivoted above the substrate 21 by electrostatic attraction forces between the electrodes and the micro-mirror 51. The micro-mirror 51 is made pivotable by a hinge (not shown) or post (not shown).

The electrodes comprise a plurality of address electrodes 30 disposed on the substrate 21, facing the micro-mirror 51, and a plurality of auxiliary electrodes 40 disposed on the substrate 21 in the vicinity of the address electrodes 30, projecting toward the micro-mirror 51.

The address electrodes 30 include first and second address electrodes 31 and 35 provided on the substrate 21, spaced a predetermined distance from each other and independently supplied with electric power.

The auxiliary electrodes 40 are provided in the vicinity of the first and second address electrodes 31 and 35, respectively, and include first and second auxiliary electrodes 41 and 45 each of which has one end projecting

beyond the micro-mirror 51, and each of which is independently supplied with electric power. Here, the first address electrode 31 and the first auxiliary electrode 41 may be independently or simultaneously supplied with electric power, and the second address 35 and the second auxiliary electrode 45 are supplied with electric power in a similar manner. In addition, the first and second auxiliary electrodes 41 and 45 are formed vertically around the outside of the first and second address electrodes 31 and 35, respectively, and each is corner shaped. In this configuration, because distances between the first and second auxiliary electrodes 41 and 45 and the micro-mirror are small and the effective surfaces of the first and second auxiliary electrodes 41 and 45 are large, electrostatic attraction forces between the first and second auxiliary electrodes 41 and 45 and the micro-mirror 51 can be strengthened.

The first and second auxiliary electrodes 41 and 45 are formed to project beyond the micro-mirror 51 as described above so that when the micro-mirror 51 is inclined in a direction, for example, toward the first auxiliary electrode 41, the distance between the opposite auxiliary electrode, i.e., the second auxiliary electrode 45 and the micro-mirror 51 can be kept small. Therefore, when the micro-mirror 51 is restored to its original position, the restoring speed of the micro-mirror 51 can be enhanced by, in addition to the restoring force of the hinge or post, an electrostatic attraction force between the second auxiliary electrode 45 and the micro-mirror 51. In this case, by applying electric power to the second address electrode 35, the restoring speed can be enhanced by an electrostatic attraction force between the second address electrode 35 and the micro-mirror 51.

The operation of the micro-mirror device having the structure as described above will be described with reference to FIGS. 6 and 7 as follows.

FIG. 6 depicts the micro-mirror 51 maintained in a horizontal position. In FIG. 6, voltages V11 and V21 applied to the first and second address electrodes 31 and 35, respectively, voltages V12 and V22 applied to the first and second auxiliary electrodes 41 and 45, respectively, and voltage V4 applied to the micro-mirror all are zero (0). Therefore, the micro-mirror 51 is maintained in a horizontal state by the strength of the hinge or post. Consequently, distances r11 and r21 between the first and second address electrodes 31 and 35 and the micro-mirror 51 are the same. Also, distances r12 and r22 between the first and second auxiliary electrodes 41 and 45 and the micro-mirror 51 are the same. Here, the distances r12 and r22 are much smaller than the distances r11 and r21, and even when the micro-mirror 51 is inclined, the distances r12 and r22 remain smaller than the distances r11 and r21 when the micro-mirror 51 is in a horizontal state.

On the other hand, when voltages V11, V21, and V4 applied to the first and second address electrodes 31 and 35 and the micro-mirror 51 have the relationship, $V11<V21<V4$, the electrostatic force F11 acting between the first address electrode 31 and the micro-mirror 51 is greater than the electrostatic force F21 acting between the second address electrode 35 and the micro-mirror 51, as shown in FIG. 7. Accordingly, the micro-mirror 51 rotates toward the first address electrode 31 side of the substrate 21, and is inclined to a position where the electrostatic force F11 is balanced by the sum of the electrostatic force F21 and the restoring force of the hinge or post, such that the condition of $r11<r21$ is satisfied. Here, voltages V12 and V22 are applied to the first and second auxiliary electrodes 41 and 45 and voltage V4 is applied to the micro-mirror 51 so that the voltages V12, V22, and V4 have the relationship

V12<V22<V4. When voltages V12 and V22 are applied as above, the voltages V12 and V22 are the same voltages applied to the first and second address electrodes **31** and **35**, respectively. In this case, the first address electrode **31** and the first auxiliary electrode **41**, and the second address electrode **35** and the second auxiliary electrode **45** are integrally formed, respectively.

In addition, when voltages V11, V21, and V4 applied to the first and second address electrodes **31** and **35** and the micro-mirror **51** respectively, have the relationship of V11>V21>V4, the result as shown in FIG. 7 can also be obtained.

The position of the micro-mirror **51** can also be changed from the position shown in FIG. 7 to the position shown in FIG. 6, or to a position where the micro-mirror **51** is inclined in a direction opposite to the position shown in FIG. 7. These operations of the micro-mirror device are described as follows.

Voltages V12, V22, and V4 which have the relationship of V22<V12<V4 are applied to the first and second auxiliary electrodes **41** and **45** and the micro-mirror **51**, respectively, so that the micro-mirror **51** is driven to be inclined in the opposite direction. In this case, the position of the micro-mirror **51** is changed by the restoring force of the hinge or post, which supports the micro-mirror **51**, and by electrostatic forces. In this case, because distances r12 and r22 between the first and second auxiliary electrodes **41** and **45** and the micro-mirror **51** are very short, and the difference between V22 and V4 exceeds the difference between V12 and V4, the electrostatic force F22 is greater than the electrostatic force F12. The time required to change the position of the micro-mirror **51** using the electrostatic attraction force between the first and second auxiliary electrodes **41** and **45** and the micro-mirror **51** can be reduced, as above.

In addition, when the slope of the micro-mirror **51** is to be changed, desired voltages, i.e., voltages V11 and V21 which have the relationship V21<V11<V4 are applied to the first and second address electrodes **31** and **35**, respectively, so that the micro-mirror **51** is driven to be inclined in a direction opposite to the direction of inclination shown in FIG. 7. In this case, because electrostatic attraction forces between the first and second auxiliary electrodes **41** and **45** and the micro-mirror **51** act in addition to the electrostatic attraction forces between the first and second address electrodes **31** and **35** and the micro-mirror **51**, the time required to change the position of the micro-mirror **51** can be further reduced. Here, voltages applied to the first address electrode **31** and the first auxiliary electrode **41** can be the same, and voltages applied to the second address electrode **35** and the second auxiliary electrode **45** can also be the same.

In addition, when the micro-mirror **51** is operated and restored, sequential application of voltages to the first and second auxiliary electrodes **41** and **45** and the first and second address electrodes **31** and **35** is possible.

Referring to FIG. 8, a micro-mirror device according to another embodiment of the present invention comprises a substrate **121**, electrodes provided on the substrate **121**, and a micro-mirror **151** supported by a hinge or post on the substrate **121** so as to be spaced a predetermined distance from the substrate **121**. The electrodes comprise address electrodes **130** disposed on the substrate **121** and spaced a predetermined distance from each other, and auxiliary electrodes **140** disposed on the substrate **121** in the vicinity of the address electrodes **130**, projecting toward the micro-mirror **151**. In this embodiment, the address electrodes **130** include first and second address electrodes **131** and **135** driven independently of each other and spaced a predetermined distance from each other. In addition, the auxiliary electrodes **140** include first and second auxiliary electrodes **141** and **145** provided in the vicinity of the first and second address electrodes **131** and **135**, respectively, for enhancing the restoring speed of the inclined micro-mirror **151** by electrostatic attraction forces. Here, because the substrate **121**, the first and second address electrode **131** and **135**, and the micro-mirror **151** are substantially the same as members described with reference to FIGS. **5** through **7**, detailed descriptions thereof are omitted.

This embodiment differs from the micro-mirror device according to the previously described embodiment in that the first and second auxiliary electrodes **141** and **145** have a cylindrical shape or a polygonal pillar shape. When the first and second auxiliary electrodes **141** and **145** are provided as above, electrostatic attraction forces can be reinforced without markedly lowering the efficiency of utilizing light, since the spaces occupied by the first and second auxiliary electrodes **141** and **145** are small, and, therefore, most of an incident beam can travel to the micro-mirror **151**.

Since the micro-mirror device having the structure described above is provided with auxiliary electrodes disposed in the vicinity of the respective address electrodes and projected toward the micro-mirror, the restoring speed of an inclined micro-mirror can be enhanced by electrostatic attraction forces between the auxiliary electrodes and the micro-mirror, and, therefore, the micro-mirror device can be widely utilized in image displaying apparatuses requiring high response speed.

The above description of the preferred embodiments has been given by way of example. From the disclosure given, those skilled in the art will not only understand the present invention and its attendant advantages, but will also find apparent various changes and modifications to the structures disclosed. It is sought, therefore, to cover all such changes and modifications as fall within the spirit and scope of the invention, as defined by the appended claims, and equivalents thereof.

What is claimed is:

1. A micro-mirror device comprising:

a substrate;

a plurality of address electrodes provided on the substrate;

at least one micro-mirror facing the substrate and spaced a predetermined distance from the substrate having a slope that is adjustable by electrostatic attraction forces between said address electrodes and said micro-mirror; and

a plurality of auxiliary electrodes formed on and projected from the substrate and having upper portions that are disposed in a vicinity of said micro-mirror,

wherein restoring force and restoring speed are enhanced by electrostatic forces of the auxiliary electrodes during restoration of an inclined micro-mirror.

2. The micro-mirror device as claimed in claim **1**, wherein the plurality of address electrodes comprises first and second address electrodes provided on the substrate and spaced a predetermined distance from each other, and the plurality of auxiliary electrodes comprises first and second auxiliary electrodes provided in the vicinity of the first and second address electrodes, respectively, and formed to project beyond the micro-mirror, and

further wherein the first and second auxiliary electrodes enhance the restoring speed of the micro-mirror by a first and a second auxiliary electrostatic attraction force, respectively, during restoration of the micro-

mirror after being inclined by a first electrostatic attraction force between the first address electrode and the micro-mirror and after being inclined by a second electrostatic attraction force between the second address electrode and the micro-mirror, respectively.

3. The micro-mirror device as claimed in claim 2, wherein the first and second auxiliary electrodes are shaped in the form of vertically erected plates.

4. The micro-mirror device as claimed in claim 2, wherein the first and second auxiliary electrodes are cylindrically shaped.

5. The micro-mirror device as claimed in claim 2, wherein the first and second auxiliary electrodes are shaped in the form of polygonal pillars.

6. The micro-mirror device as claimed in claim 2, wherein a first voltage is applied to the first address electrode and to the first auxiliary electrode, when the position of the micro-mirror is changed.

7. The micro-mirror device as claimed in claim 6, wherein the first address electrode and the first auxiliary electrode are integrally formed.

8. The micro-mirror device as claimed in claim 2, wherein a second voltage is applied to the second address electrode and to the second auxiliary electrode, when the position of the micro-mirror is changed.

9. The micro-mirror device as claimed in claim 8, wherein the second address electrode and the second auxiliary electrode are integrally formed.

10. A method of driving a micro-mirror device to rotate from a horizontal position to an inclined position and to restore the micro-mirror device to the horizontal position, said method comprising:

applying a first address voltage (V11) to a first address electrode provided on a substrate;

applying a second address voltage (V21) to a second address electrode provided on the substrate and spaced a predetermined distance from the first address electrode;

applying a first mirror voltage (V41) to a micro-mirror facing the substrate and spaced a predetermined distance from the substrate, such that the micro-mirror device rotates toward the inclined position;

applying a first auxiliary voltage (V12) to a first auxiliary electrode formed on and projected from the substrate and having upper portions that are disposed in a vicinity of the micro-mirror;

applying a second auxiliary voltage (V22) to a second auxiliary electrode formed on and projected from the substrate and having upper portions that are disposed in a vicinity of the micro-mirror; and

applying a second mirror voltage (V42) to the micro-mirror, such that the micro-mirror device rotates toward the horizontal position.

11. The method of driving a micro-mirror device as claimed in claim 10, wherein the voltages V11, V21, and V41 have a relationship $V11<V21<V41$ causing the micro-mirror device to rotate toward a first electrode side of the substrate, and wherein the voltages V22, V12, and V42 have a relationship $V22<V12<V42$ causing the micro-mirror device to rotate toward the horizontal position.

* * * * *

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Hornbeck

(10) **Patent No.: US 6,323,982 B1**
(45) **Date of Patent: Nov. 27, 2001**

(54) **YIELD SUPERSTRUCTURE FOR DIGITAL MICROMIRROR DEVICE**

(75) Inventor: **Larry J. Hornbeck**, Van Alstyne, TX (US)

(73) Assignee: **Texas Instruments Incorporated**, Dallas, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/309,745**

(22) Filed: **May 11, 1999**

Related U.S. Application Data

(60) Provisional application No. 60/086,453, filed on May 22, 1998.

(51) **Int. Cl.**[7] G02B 26/08
(52) **U.S. Cl.** **359/224**; 359/223; 359/900; 359/198
(58) **Field of Search** 359/223, 224, 359/290–291, 295, 298, 198, 900

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Application No. 08/483,777 filed Jun. 7, 1995.

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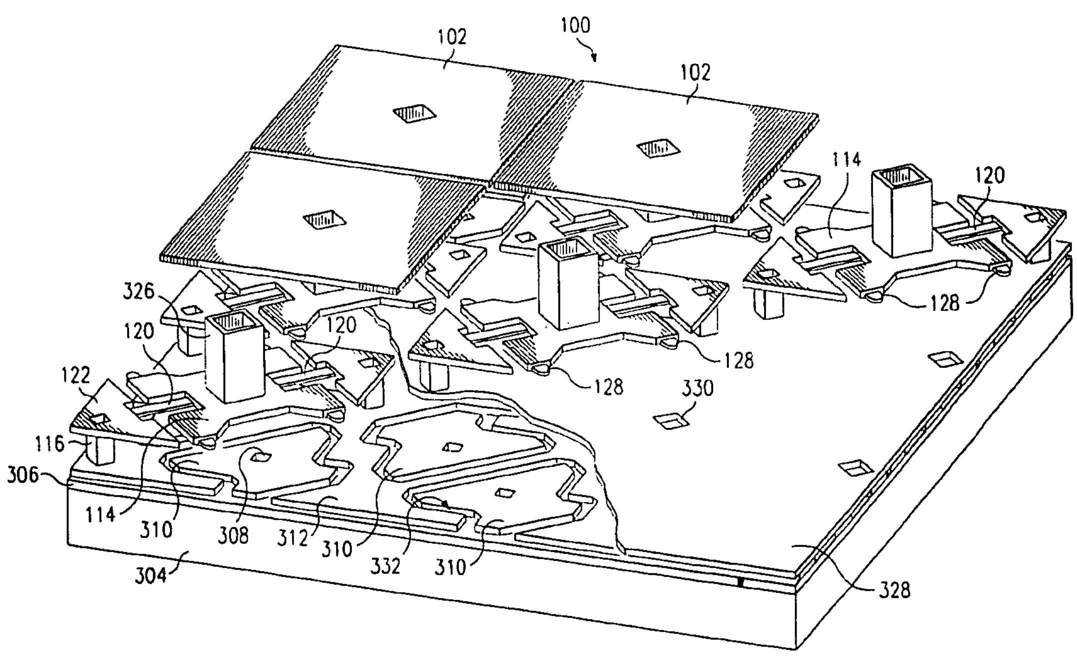
Primary Examiner—James Phan
(74) *Attorney, Agent, or Firm*—Charles A. Brill; Wade James Brady, III; Frederick J. Telecky, Jr.

(57) **ABSTRACT**

A high-yield micromirror device and fabrication method. Address electrodes (**310**) and a separate mirror bias/reset conductor (**312**) are disposed on a substrate (**304**). A micromirror superstructure including torsion beam support posts (**116**), torsion beam hinges (**120**), a torsion beam yoke (**114**), a mirror support post (**326**), and a mirror (**102**) is fabricated above, and electrically connected to, the mirror bias/reset conductor (**312**) such that the torsion beam yoke (**114**) and mirror (**102**) are suspended above the address electrodes (**310**). A dielectric layer (**328**) is formed over the address electrodes (**310**). The dielectric layer (**328**), coupled with the elimination of upper address electrodes used in the prior art electrically insulates the address electrodes (**310**) from contact with the mirror superstructure and prevents conductive debris from shorting either the mirror superstructure or mirror bias/reset conductor (**312**) to the address electrodes (**310**).

30 Claims, 7 Drawing Sheets



07/17/2002, EAST Version: 1.03.0002

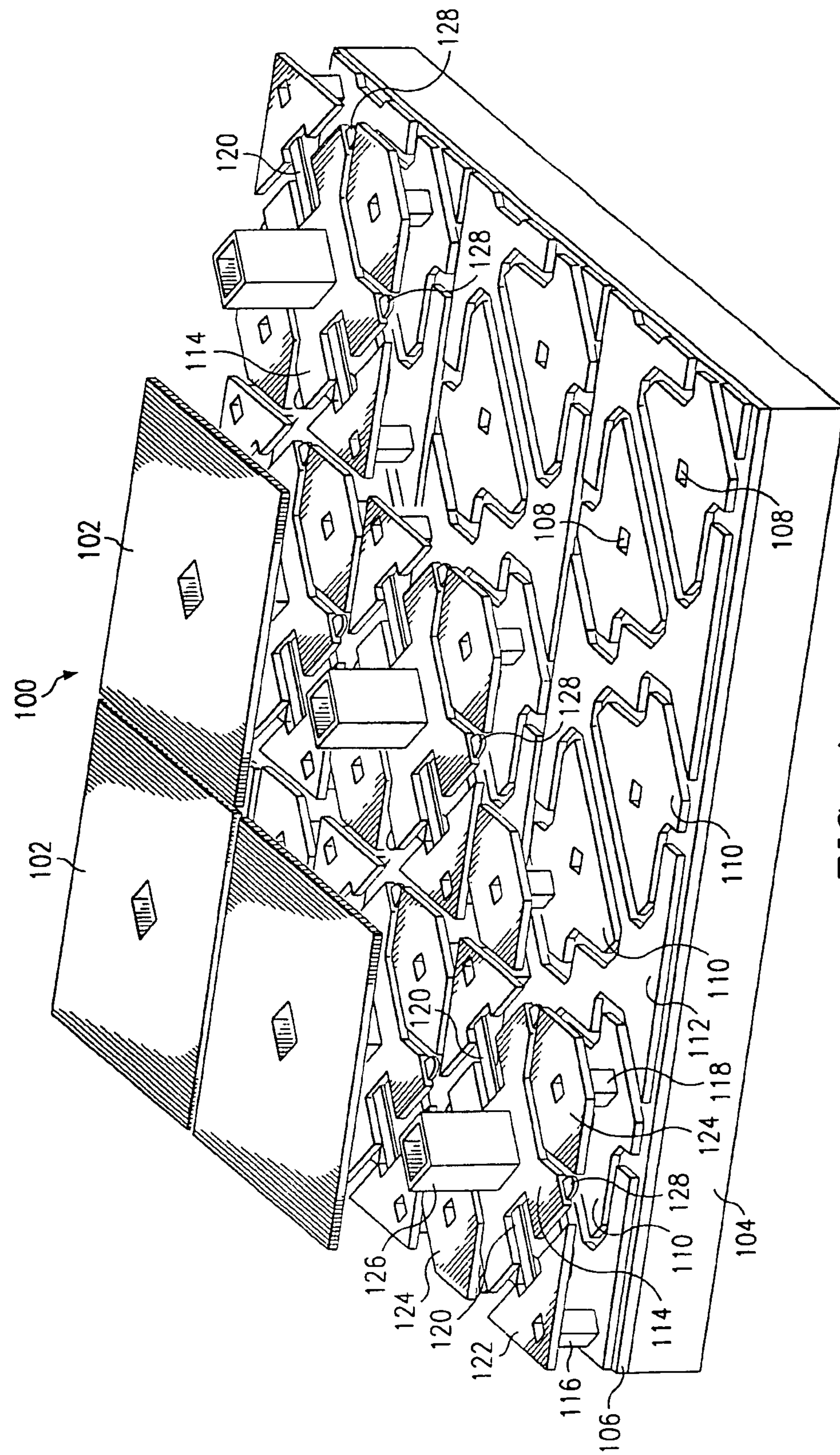


FIG. 1
(PRIOR ART)

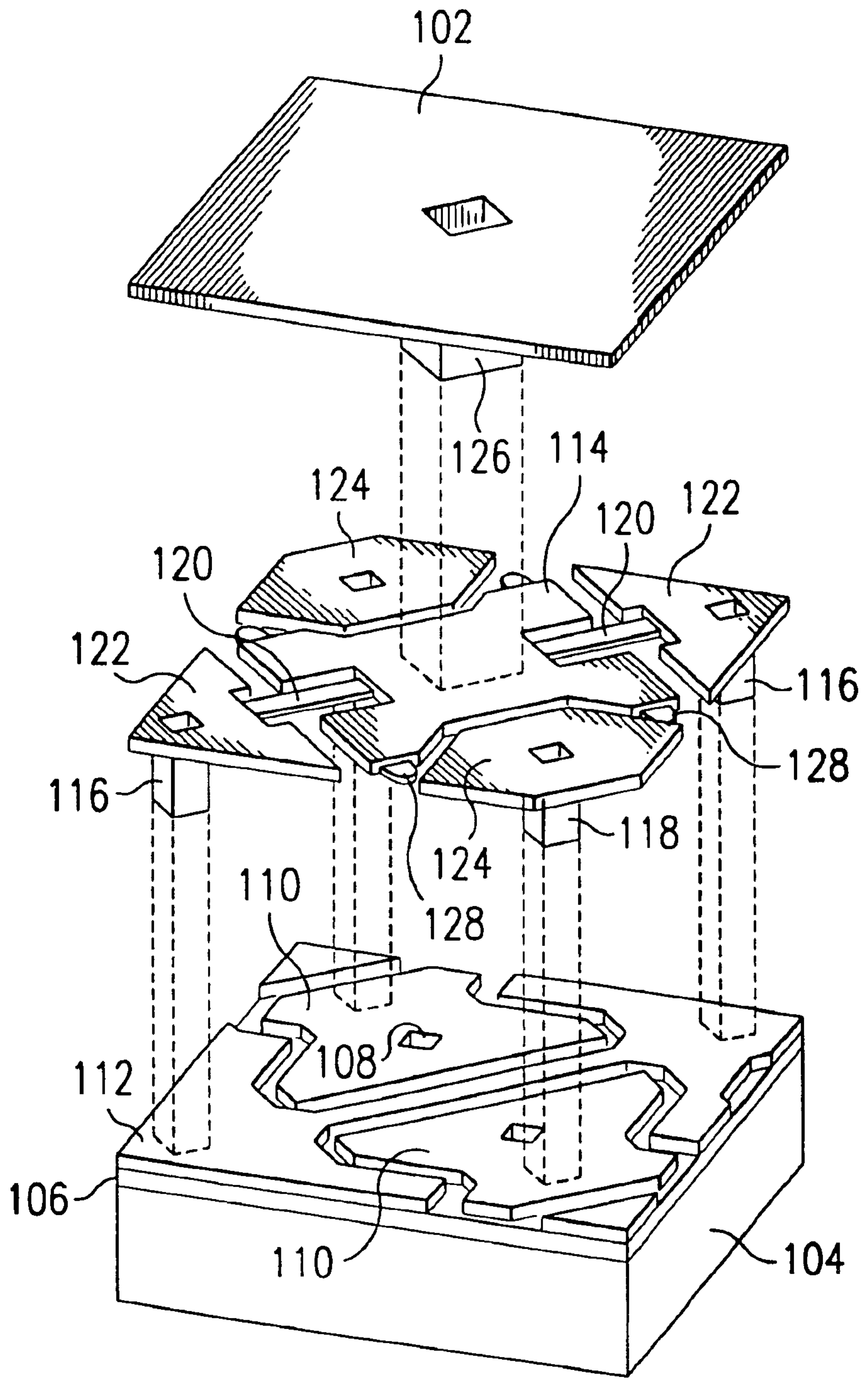


FIG. 2
(PRIOR ART)

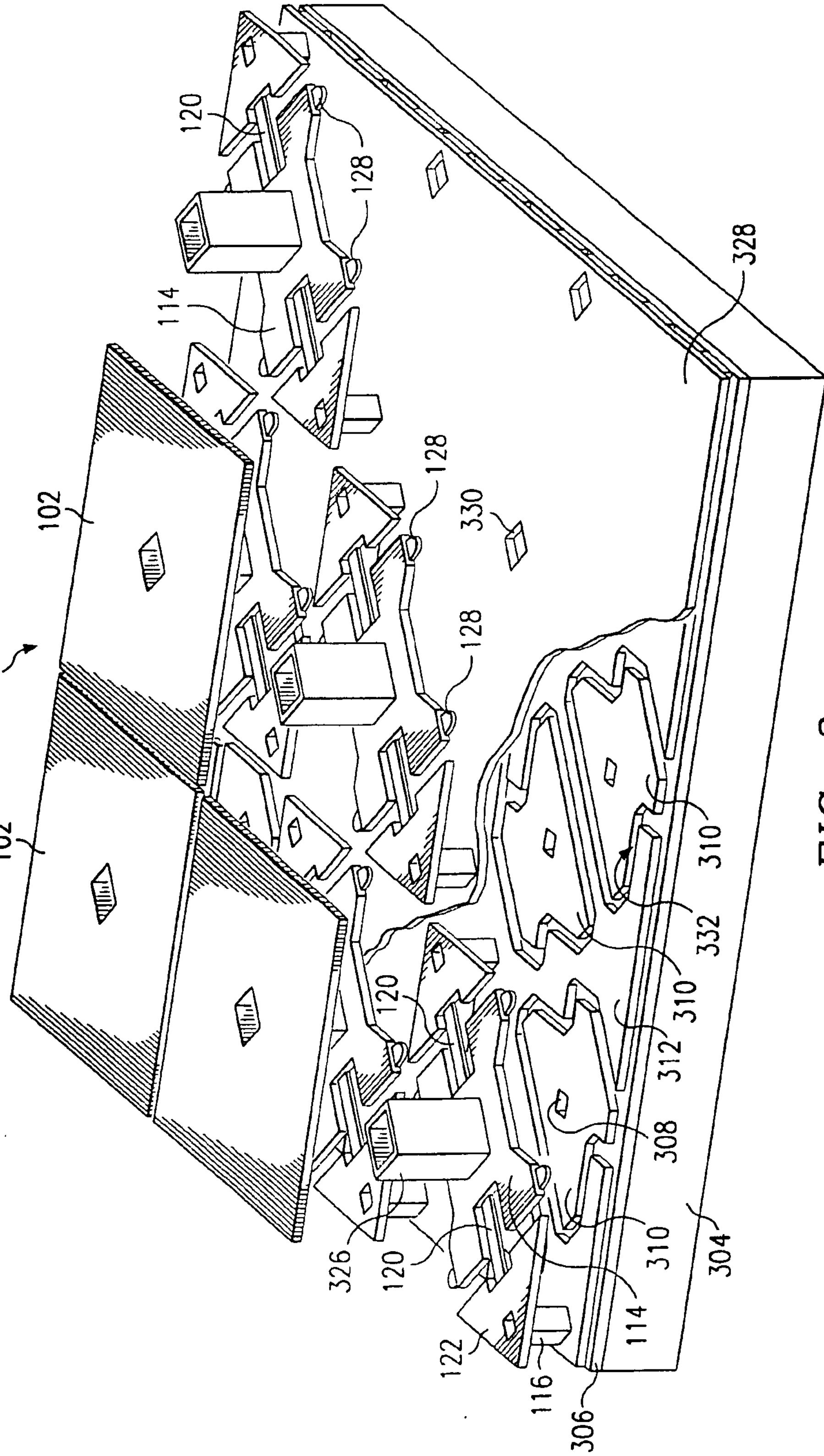

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FIG. 3

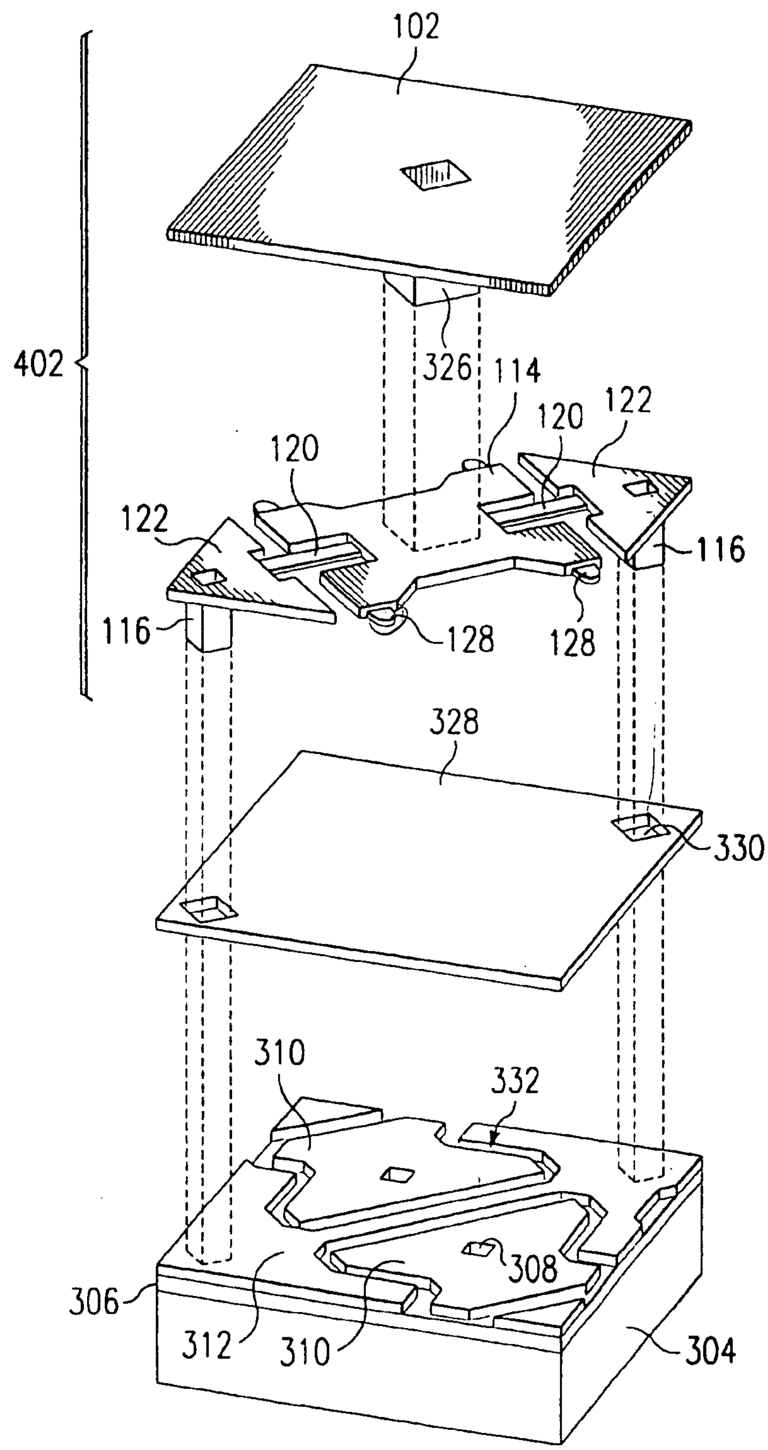
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FIG. 4

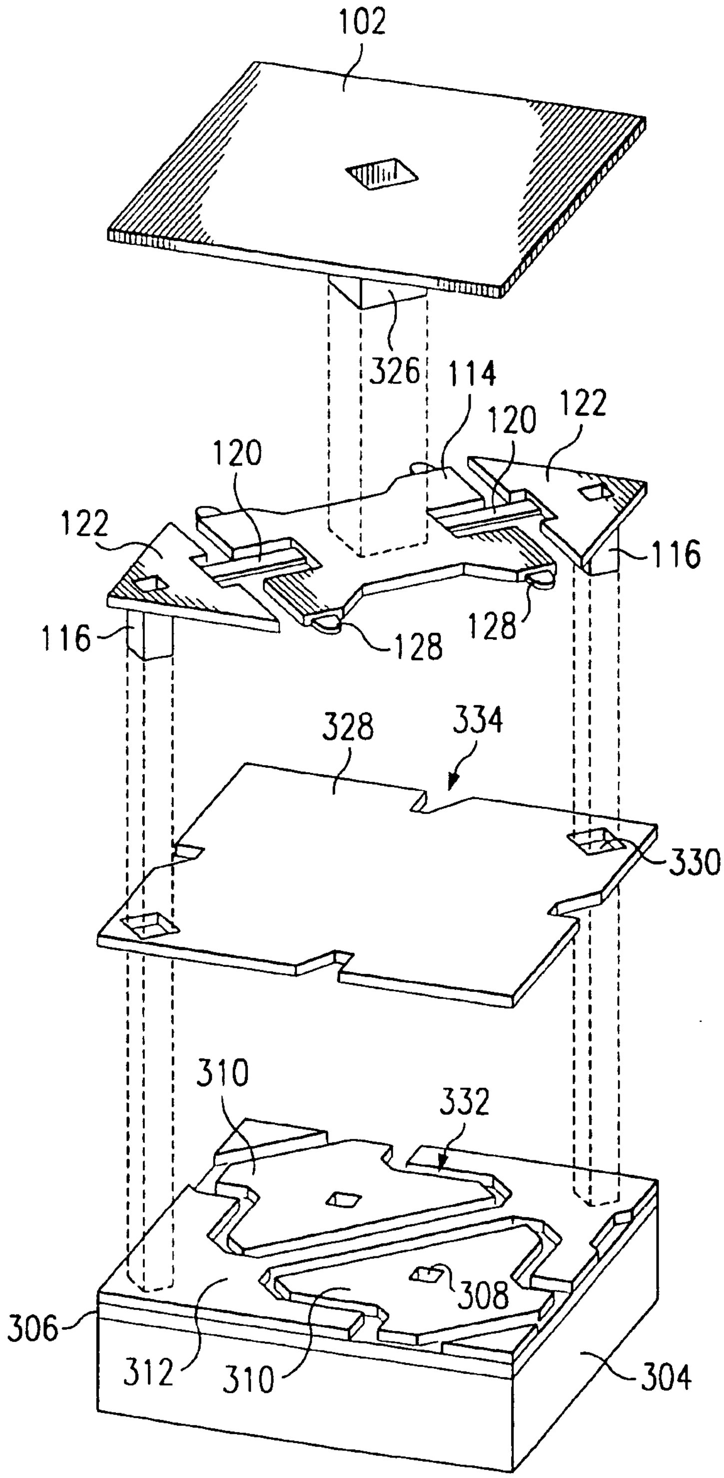
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FIG. 5

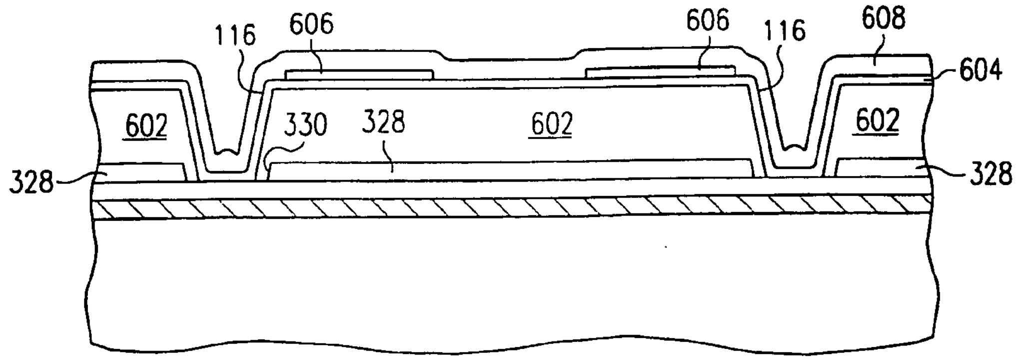

FIG. 6

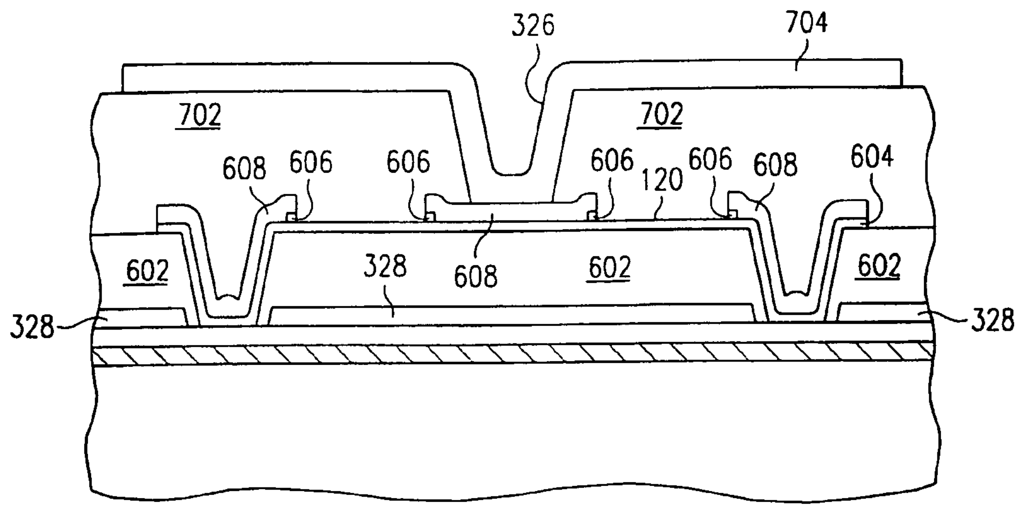

FIG. 7

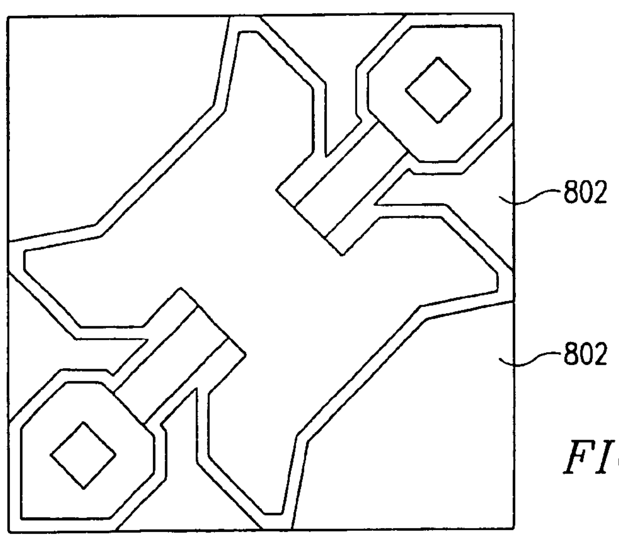

FIG. 8

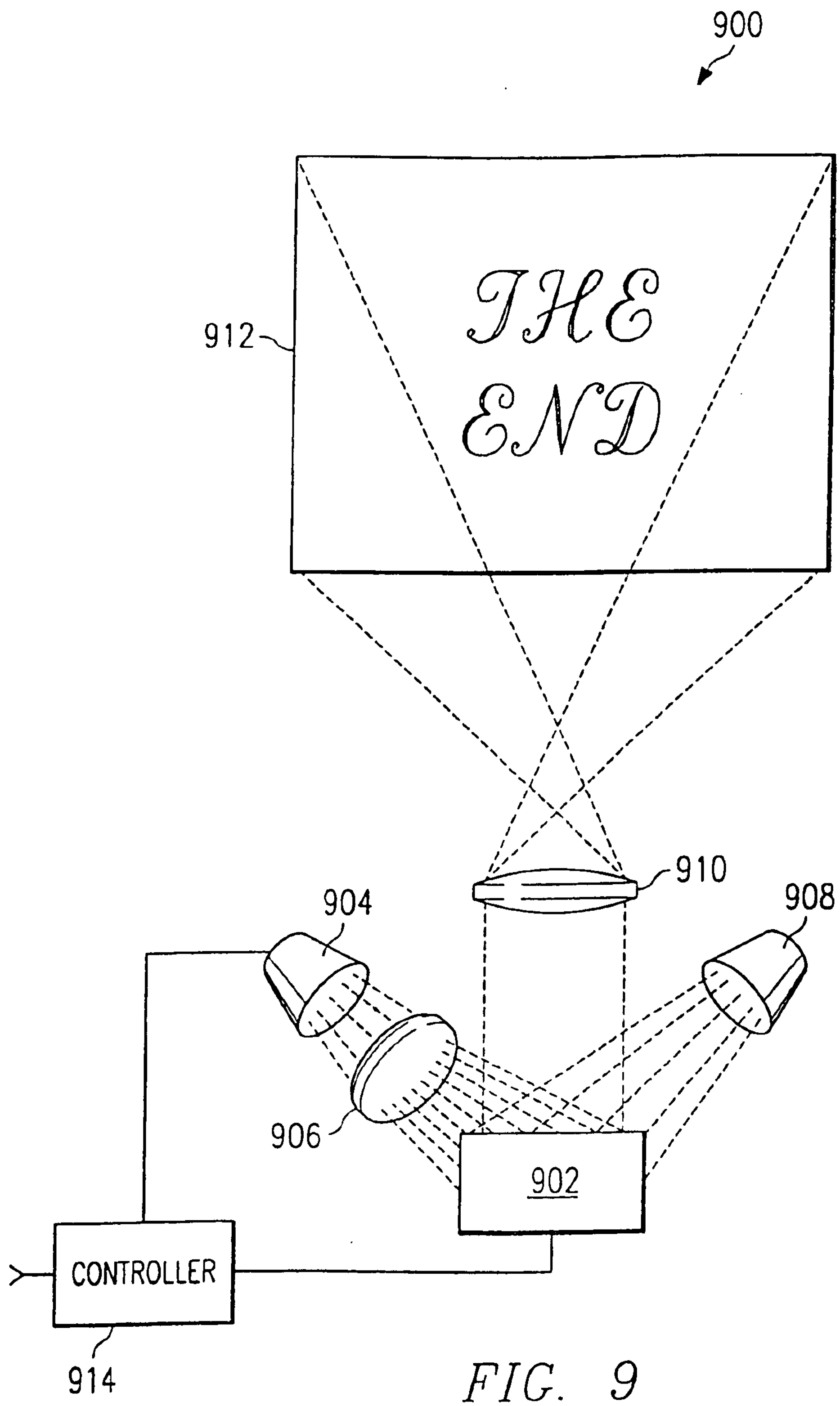

FIG. 9

YIELD SUPERSTRUCTURE FOR DIGITAL MICROMIRROR DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 USC §119(e)(1) of provisional application No. 60/086,453 filed May 22, 1998.

The following patents and/or commonly assigned patent applications are hereby incorporated herein by reference:

Patent No.	Filing Date	Issue Date	Title
5,096,279	Nov. 26, 1990	Mar. 17, 1992	Spatial Light Modulator And Method
5,583,688	Dec. 21, 1993	Dec. 10, 1996	Multi-Level Digital Micromirror Device

FIELD OF THE INVENTION

This invention relates to the field of micromechanical devices, more particularly to digital micromirror devices.

BACKGROUND OF THE INVENTION

Micromechanical devices are small structures typically fabricated on a semiconductor wafer using techniques such as optical lithography, metal sputtering, plasma oxide deposition, and plasma etching which have been developed for the fabrication of integrated circuits.

Digital micromirror devices (DMDs), sometimes referred to as deformable mirror devices, are a type of micromechanical device. Other types of micromechanical devices include accelerometers, pressure and flow sensors, gears and motors. While some micromechanical devices, such as pressure sensors, flow sensors, and DMDs have found commercial success, other types have not yet been commercially viable.

Digital micromirror devices are primarily used in optical display systems. In display systems, the DMD is a light modulator which uses digital image data to modulate a beam of light by selectively reflecting portions of the beam of light to a display screen. While analog modes of operation are possible, DMDs are typically operated in a digital bistable mode of operation and as such are the core of the first true digital full-color image projection systems.

Micromirrors have evolved rapidly over the past ten to fifteen years. Early devices used a deformable reflective membrane which, when electrostatically attracted to an underlying address electrode, dimpled toward the address electrode. Schlieren optics were used to illuminate the membrane and create an image from the light scattered by the dimpled portions of the membrane. Schlieren systems enabled the membrane devices to form images, but the images formed were very dim and had low contrast ratios, making them unsuitable for most image display applications.

Later micromirror devices used flaps or diving board-shaped cantilever beams of silicon or aluminum, coupled with dark-field optics to create images having improved contrast ratios. Flap and cantilever beam devices typically used a single metal layer to form the top reflective layer of the device. This single metal layer bent downward over the length of the flap or cantilever when attracted by the underlying address electrode, creating a curved surface. The

curved surface scattered incident light—lowering the contrast ratio of images formed with flap or cantilever beam devices.

Torsion beam devices were developed to improve the image contrast ratio by concentrating the deformation on a relatively small portion of the DMD surface. Torsion beam devices use a thin metal layer to form a torsion beam, which is often referred to as a torsion hinge, and a thicker metal layer to form a rigid member. The thicker rigid member, which is sometimes referred to as a torsion beam or simply a beam, typically has a mirror-like surface. The rigid mirror remains flat while the torsion hinges deform, minimizing the amount of light scattered by the device and improving the contrast ratio of the device.

Recent micromirror configurations, called hidden-hinge designs, further improve the image contrast ratio by using an elevated mirror to block most of the light from reaching the device superstructure. The elevated mirror is connected by a support post to an underlying torsion beam or yoke. The yoke is attached to torsion hinges which in turn are connected to rigid support posts. Because the structures which support the mirror and allow it to rotate are underneath the mirror instead of around the perimeter of the mirror, virtually the entire surface of the device is used to fabricate the mirror. Since virtually all of the light striking a hidden-hinge micromirror device reaches an active mirror surface—and thus either used to form an image pixel or reflected away from the image to a light trap—the hidden-hinge device's contrast ratio is much higher than the contrast ratio of previous devices.

Micromirror devices are generally operated in one of two modes of operation. The first mode of operation is an analog mode, sometimes called beam steering, wherein the address electrode is charged to a voltage corresponding to the desired deflection of the mirror. Light striking the micromirror device is reflected by the mirror at an angle determined by the deflection of the mirror. Depending on the voltage applied to the address electrode, the cone of light reflected by an individual mirror is directed to fall outside the aperture of a projection lens, partially within the aperture, or completely within the aperture of the lens. The reflected light is focused by the lens onto an image plane, with each individual mirror corresponding to a location on the image plane. As the cone of reflected light is moved from completely within the aperture to completely outside the aperture, the image location corresponding to the mirror dims, creating continuous brightness levels.

The second mode of operation is a digital mode. When operated digitally, each micromirror is fully deflected in either of the two directions about the torsion hinge axis. Digital operation uses a relatively large address voltage to ensure the mirror is fully deflected. The address electrodes are driven using standard logic voltage levels and a bias voltage, typically a positive voltage, is applied to the mirror metal layer to control the voltage difference between the address electrodes and the mirrors. Use of a sufficiently large mirror bias voltage, a voltage above what is termed the threshold voltage of the device, ensures the mirror will fully deflect toward the address electrode—even in the absence of an address voltage. The use of a large mirror bias voltage enables the use of low address voltages since the address voltages need only slightly deflect the mirror prior to the application of the large mirror bias voltage.

To create an image using the micromirror device, the light source is positioned at an angle relative to the device normal equal to twice the angle of rotation so that mirrors rotated

toward the light source reflect light in a direction normal to the surface of the micromirror device and into the aperture of a projection lens—creating a bright pixel on the image plane. Mirrors rotated away from the light source reflect light away from the projection lens—leaving the corresponding pixel dark. Intermediate brightness levels are created by pulse width modulation techniques in which the mirror rapidly is rotated on and off to vary the quantity of light reaching the image plane. The human eye integrates the light pulses and the brain perceives a flicker-free intermediate brightness level.

Full-color images are generated by using three micromirror devices to produce three single-color images, or by sequentially forming three single-color images using a single micromirror device illuminated by a beam of light passing trough three color filters mounted on a rotating color wheel.

While demand for micromirror-based display systems is created primarily as a result of the superior image quality the systems provide, some market segments are characterized by cost concerns more than image quality concerns. Micromirror devices are produced in bulk on semiconductor wafers and therefore take advantage of the same wafer processing economies of scale which characterize the semiconductor industry. Wafer processing places great emphasis on the wafer yield—the number of working devices produced by each wafer. Therefore, methods of increasing the wafer yield are needed.

SUMMARY OF THE INVENTION

Objects and advantages will be obvious, and will in part appear hereinafter and will be accomplished by the present invention which provides a method and system for a high-yield micromirror device. According to one embodiment of the disclosed invention, a micromirror device is disclosed. The micromirror device comprises a substrate, at least one address electrode and mirror bias/reset conductor supported by the substrate, and a dielectric layer overlying at least one address electrode. A deflectable rigid member is supported over the substrate by a deformable element. In operation, a voltage differential between the address electrode and the rigid member is operable to create an electrostatic attraction between the address electrode and the rigid member thus causing the deflectable rigid member to deflect toward said address electrode.

According to another embodiment of the disclosed invention, a method of forming a micromirror device is disclosed. The method comprises the steps of forming a mirror bias/reset conductor and address electrodes on a substrate, forming a dielectric layer over the address electrodes, and forming a deflectable rigid member supported by the substrate.

According to yet another embodiment of the disclosed invention., a method of forming a micromirror device is disclosed. The method comprises the steps of forming a mirror bias/reset conductor and address electrodes on a substrate, forming a dielectric layer over the address electrodes between the address electrodes and mirror bias/reset conductor, depositing a first spacer layer, depositing at least one metal layer on the first spacer layer, patterning the at least one metal layer to form the support structures, a deformable element, and a hinge yoke, forming a second spacer layer over portions of the first spacer layer not covered by the support structures, the deformable element, and the hinge yoke, depositing a third spacer layer over the second spacer layer, the support structures, the deformable element, and the hinge yoke, opening vias through the third spacer layer to the hinge yoke, and forming micromirrors on the third spacer layer.

The disclosed invention also provides a micromirror device comprising a substrate, a first layer supported by the substrate, a second layer forming a micromirror spaced apart from the first layer, and a third layer disposed between said first layer and said second layer. The third layer is supported by the substrate and in turn supports the second layer. The third layer forms at least one deformable element and at least one hinge yoke, and address electrodes are formed only in said first layer.

The disclosed invention also provides a method of forming a micromirror device, comprising the steps of forming a mirror bias/reset conductor and address electrodes on a substrate, forming a hinge yoke supported above the address electrodes, and forming a micromirror supported by said hinge yoke.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a perspective view of a small portion of a micromirror array of the prior art.

FIG. 2 is an exploded perspective view of a single micromirror element from the micromirror array of FIG. 1.

FIG. 3 is a perspective view of a small portion of an improved micromirror array according to one embodiment of the present invention.

FIG. 4 is an exploded perspective view of a single micromirror element from the micromirror array of FIG. 3.

FIG. 5 is an exploded perspective view of a single micromirror element similar to the element of FIG. 4, but with holes in the dielectric layer to allow the torsion hinge yoke to land on the mirror bias/reset metalization layer.

FIG. 6 is a cross-section view along the torsion hinge axis showing a partially fabricated improved micromirror element of FIG. 3 prior to etching the torsion hinges and yoke.

FIG. 7 is a cross-section view along the torsion hinge axis showing the element of FIG. 6 prior to etching away the sacrificial spacer layers.

FIG. 8 is a top view of a partially completed micromirror element according to the present invention showing an inverse yoke region spacer.

FIG. 9 is a schematic view of a micromirror-based projection system utilizing an improved micromirror device according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A new micromirror architecture has been developed that is capable of greatly increasing device yield, with only a slight increase in the processing steps required to implement the improved architecture. In addition to improving the initial yield of working devices, the disclosed architecture also increases the device's resistance to failures during the operation of the device caused by particle contamination during the operation of the device.

Although the disclosed invention will be discussed primarily in terms of modern hidden-hinge device architectures, this emphasis is solely for the purposes of showing the application of the inventive concepts to the

most commercially promising designs. The concepts of the disclosed invention may be applied to all architectures of micromirror designs.

A typical hidden-hinge DMD 100 is an orthogonal array of DMD cells, or elements. This array often includes more than a thousand rows and columns of DMD cells. FIG. 1 shows a small portion of a DMD array with several mirrors 102 removed to show the underlying mechanical structure of the DMD array. FIG. 2 is an exploded view of a single DMD element further detailing the relationships between the DMD structures.

A DMD is fabricated on a semiconductor, typically silicon, substrate 104. Electrical control circuitry is typically fabricated in or on the surface of the semiconductor substrate 104 using standard integrated circuit process flows. This circuitry typically includes, but is not limited to, a memory cell associated with and typically underlying each mirror 102, voltage driver circuits to drive bias and reset signals to the mirror superstructure, and digital logic circuits to control the transfer of the digital image data to the underlying memory cells. Data formatting logic could also be formed in the substrate 104. In the past, some DMD configurations used a split reset configuration, also known as memory-multiplexed addressing, which allowed several DMD elements to share one memory cell—thus reducing the number of memory cells necessary to operate a very large array, and making more room available for voltage driver and image processing circuitry on the DMD integrated circuit. Split reset is enabled by the bistable operation of a DMD, which allows the contents of the underlying memory to change without affecting the position of the mirror 102 when the mirror has a bias voltage applied.

The silicon substrate 104 and any necessary metal interconnection layers are isolated from the DMD superstructure by an insulating layer 106 which is typically a plasma deposited oxide. This layer is planarized by a chemical/mechanical polish (CMP) to provide an optically flat surface upon which to build the DMD superstructure. Holes or vias 108 are opened in the oxide layer to allow electrical connection of the DMD superstructure with the electronic circuitry formed in the substrate 104. Vias 108 are called Via2 because there is an earlier via layer formed in the underlying electronic circuitry.

The first layer of the superstructure is a metalization layer. Because two metalization layers are typically required to interconnect the circuitry fabricated on the substrate, the first layer of the superstructure is typically the third metalization layer, often called Metal3. The Metal3 metalization layer is deposited on the insulating layer 106 and patterned to form address electrodes 110 and a mirror bias connection 112. The address electrodes 110 are electrically connected to the underlying electronic circuitry through the vias 108.

Due to the voltage potential between the mirror 102 and the address electrodes, contact between the mirror 102 and either the upper or lower address electrodes 124, 110 could fuse the torsion hinges 120 or weld the mirror 102 to the address electrodes—in either case ruining the DMD. Micromirrors are designed to prevent contact between the rotating structure and the address electrodes by keeping the lower address electrodes 110 away from the regions where the rotating structure, including the mirror 102 and the hinge yoke 114 contacts the substrate, and by increasing the elevation of the mirror and shaping the upper address electrodes 124 to minimize interference between the mirror 102 and the upper address electrodes 124.

The regions where the rotating structure, typically hinge yoke 114, contacts the substrate or structures on the substrate are called landing sites. Landing sites mechanically limit the rotation of the mirror 102 or hinge yoke 114. Elastic extensions of the hinge yoke, called spring tips 128, localize contact between the hinge yoke 114 and the landing sites. The landing sites are often coated with a material chosen to reduce the tendency of the mirror 102 and torsion hinge yoke 114 to stick to the landing site. Some micromirror designs have metallized landing sites, called landing electrodes, that are separate and distinct from, but electrically connected to, the mirror bias connection 112. Other micromirror designs pattern the mirror bias connection 112 to include integral landing sites. Since the same voltage is always applied to both the landing sites and the mirrors 102, the mirror bias connection and the landing electrodes are preferably combined in a single structure when possible.

Mirror bias/reset voltages travel to each mirror 102 through the mirror bias/reset conductor, typically a mirror bias/reset metalization layer 112. Some reset designs require the array of mirrors to be subdivided into multiple sub-arrays each having an independent mirror bias connection. The landing electrode/mirror bias 112 configuration shown in FIG. 1 is ideally suited to split reset applications since the DMD elements are easily segregated into electrically isolated rows or columns simply by isolating the mirror bias/reset layer between the sub-arrays.

A first layer of supports, typically called spacervias, is fabricated on the metal layer forming the address electrodes 110 and mirror bias connections 112. These spacervias, which include both torsion hinge support spacervias 116 and upper address electrode spacervias 118, are typically formed by spinning a thin spacer layer over the address electrodes 110 and mirror bias connections 112. This thin spacer layer is typically a 1 μm thick layer of positive photoresist. After the photoresist layer is soft baked, it is exposed, developed, and deep UV hardened to form holes where the spacervias will be formed. This spacer layer, as well as a thicker spacer layer used later in the fabrication process, are often called sacrificial layers since they are used only as forms during the fabrication process and are removed from the device prior to device operation.

A thin layer of metal, typically an aluminum alloy, is sputtered onto the spacer layer and into the holes. An oxide is then plasma deposited over the thin metal layer and patterned to form etch stops over the regions that later will form torsion hinges 120. A thick layer of metal, typically an aluminum alloy, is sputtered over the thin layer and oxide etch stops. Another layer of oxide is grown and patterned to define the torsion hinge yoke 114, hinge support caps 122 (typically considered part of the hinge support post 116), and the upper address electrodes 124. After this second oxide layer is patterned, the two metals layers are etched simultaneously and the oxide etch stops removed to leave thick rigid torsion hinge yokes 114, hinge support posts 116, upper address electrodes 124, and thin flexible torsion hinges 120.

A thick spacer layer is then deposited over the thick metal layer and patterned to define holes in which mirror support spacervias 126 will be formed. The thick spacer layer is typically a 2.4 μm thick layer of positive photoresist. A thick layer of mirror metal, typically an aluminum alloy, is sputtered on the surface of the thick spacer layer and into the holes in the thick spacer layer. The thick metal layer is then patterned to form the mirrors 102 and both spacer layers are removed using a plasma etch.

Once the two spacer layers have been removed, the mirror is free to rotate about the axis formed by the torsion hinge. Electrostatic attraction between an address electrode 110 and

a deflectable rigid member, which in effect form the two plates of an air gap capacitor, is used to rotate the mirror structure. The upper address electrodes 124 also electrostatically attract the deflectable rigid member. The term deflectable rigid member is used to encompass all of the moveable elements of the device, other than the torsion hinges 120, regardless of the architecture of the device. Depending on the design of the micromirror, the term deflectable rigid member includes the torsion hinge yoke 114, mirror beam 102, both the yoke 114 and mirror beam 102, or a mirror beam attached directly to the torsion hinges. The torsion hinges 120 which support the deflectable rigid member are a deformable member—a term which include s structures enabling other forms of motion such as cantilever hinges.

The force created by the voltage potential is a function of the square of the reciprocal of the distance between the two plates. As the rigid member rotates due to the electrostatic torque, the torsion hinges resist with a restoring torque which is an approximately linear function of the angular deflection of the torsion hinges. The structure rotates until the restoring torsion hinge torque equals the attracting electrostatic torque. As mentioned above, most micromirror devices are operated in a digital mode wherein sufficiently large bias voltages are used to ensure full deflection of the micromirror superstructure.

FIG. 3 is a perspective view of a small portion of a micromirror array according to one embodiment of the disclosed invention. FIG. 4 is an exploded perspective view of the one element or cell of FIG. 3, showing the interrelationship of the various layers in the device.

Fabrication of the dielectrically isolated hidden-hinge micromirror device is similar to previous hidden-hinge fabrication processes through the Via2 formation. This process yields a substrate 304 having electrical circuitry, typically CMOS circuitry, fabricated in the surface, and two layers of metalization sealed by a CMP oxide. The Via2 308 step opens holes in the oxide layer over the second metalization layer to allow the address electrodes of the micromirror to electrically connect to the underlying circuitry.

A third metal layer, Metal3, is sputtered over the CMP oxide and into the Via2 308 openings to the Metal2 layer. Metal3 is typically a 3000 Å thick layer of an aluminum alloy. After depositing Metal3, it is patterned and etched to form a mirror bias/reset structure 312 and address electrodes 310.

After patterning the Metal3 layer, a 0.2 μm thick layer of oxide is formed over the entire Metal3 layer to form a dielectric insulation layer 328. This oxide layer 328 is typically a plasma oxide, but may be formed by other techniques. This oxide layer 328 acts not only as an insulator to prevent shorts between the micromirror superstructure and the underlying Metal3 layer, but also as a dielectric layer between the address electrode 310 and the torsion hinge yoke 114 and mirror 102. Holes 330 or vias (often called Via3) are opened in the dielectric layer 328 to permit electrical connection of the superstructure to the Metal3 layer.

According to one embodiment of the disclosed invention, shown in FIGS. 3 and 4, rotation of the deflectable rigid member is stopped by contact between the deflectable rigid member and the dielectric insulation layer 328. As the torsion hinge yoke 114 rotates about the torsion hinge axis, spring tips 128 will contact the dielectric insulation layer 328 and stop the rotation of the deflectable rigid member—thus avoiding contact between the torsion hinge yoke 114 and the landing sites on the mirror bias/reset metalization layer 312.

According to a second embodiment of the disclosed invention, shown in FIG. 5, holes 334 are opened through the dielectric isolation layer 328 to allow the spring tips 128 to contact the landing sites on the mirror bias/reset metalization layer 312. The holes shown in FIG. 5 do not expose the address electrodes 310—thus maintaining a high resistance to particulate-caused shorts provided by the dielectric isolation layer 328 without interfering with the traditional means of stopping mirror rotation. The size, shape, and location of the holes 334 shown in FIG. 5 illustrate only one example of many hole patterns which could be used.

According to yet another embodiment of the disclosed invention, only the address electrodes 310 are covered by the dielectric layer 328. Covering only the address electrodes provides protection from electrical short circuits since the exposed mirror bias/reset metalization layer 312 and the mirror superstructure share a common voltage. Portions of the gap 332 between the address electrodes 310 and the mirror bias/reset metalization 312 may also be covered with the dielectric layer 328 to ensure complete coverage of the address electrodes 310.

If the gaps 332 between the address electrodes 310 and the mirror bias/reset metalization layer 312 are 2 μm or larger, a plasma oxide will not provide a sufficiently planar surface on which to fabricate the remainder of the micromirror device. Height variations in the layers on which the overlying micromirror superstructure is fabricated result in a non-planar micromirror and degrade the image formed by the micromirror device. To provide a planar dielectric layer on which to fabricate the remainder of the device, a plasma oxide layer thicker than 0.2 μm is formed and planarized using a CMP process. Alternatively, two separate oxide layers are used to provide a planar oxide surface: a first oxide layer deposited and patterned to fill the gaps between the address electrodes 310 and the mirror bias/reset metalization layer 312 and a second oxide layer deposited over the first oxide layer, the address electrodes 310 and the mirror bias/reset metalization layer 312.

A thick planarizing spacer layer 602, shown in FIG. 6, is formed over the dielectric insulation layer 328. This first spacer layer is typically a 1 μm thick positive photoresist which is spun onto the substrate wafer. The first spacer layer 602 is then patterned to form vias which will act as forms for the torsion hinge support spacervias 116, and deep UV hardened to prevent bubbling and deformation during later processing steps. The spacervias 116 are nested inside the Via3 330 holes to permit electrical connection between the micromirror superstructure 402 and the mirror bias/reset structure 312.

A layer of torsion hinge metal 604 is sputtered over the first spacer layer and into the spacervias, making electrical contact with the Metal3 layer. The torsion hinge metal layer is typically a 600 Å thick aluminum alloy layer. Oxide torsion hinge etch stops 606 are formed over the regions which will later form the torsion hinges 120, and a second layer of metal 608, typically a 4000 Å thick aluminum alloy layer, is sputtered over the torsion hinge layer and etch stops. Both the first and second metal layers are then etched in a single step to form torsion hinge support posts 116, torsion hinges 120, and yokes 114.

Prior hidden-hinge micromirror designs, shown in FIGS. 1 and 2, used two address electrodes on each side of the torsion hinge axis. A lower address electrode 110 electrostatically attracted the torsion hinge 120 while an upper address electrode 124 electrostatically attracted the mirror 102. The upper address electrode 124 was fabricated at the

same level, and during the same process steps, as the torsion hinge supports **116**, the torsion hinge support caps **122**, the torsion hinge **120**, and the torsion hinge yoke **114**. The disclosed architecture eliminates the elevated upper address electrodes **124**, thus physically and electrically isolating all superstructure components that are biased by address voltages from the components that are biased by mirror bias/reset voltages.

Elimination of the upper address electrodes **124** enables several reliability improvements to the micromirror device. First, the elimination of the upper address electrodes **124** eliminates the possibility of debris in the micromirror package wedging between the torsion hinge yoke **114** and the upper address electrode **124**. Debris wedging between the torsion hinge yoke **114** and the upper address electrode **124** may electrically short circuit the device as well as mechanically obstruct movement of the mirror.

Elimination of the upper address electrodes **124** enables the use of relaxed design rules which result in larger gaps between various elements of the micromirror structure. These larger gaps, in addition to being less susceptible to shorting debris, reduce the likelihood of a poor etch process leaving metal filaments that extend across gaps between structural elements. Thus, the elimination of the upper address electrodes **124** increases fabrication yields by increasing the tolerance of the device to variations in the fabrication processes.

Elimination of the upper address electrodes **124** also allows the use of a shorter mirror support spacervia **326** since the rotated mirror **102** no longer needs to avoid conflict with the upper address electrodes **124**. The height of the mirror support spacervia **326** is controlled by the thickness of a second spacer layer **702**, shown in FIG. **7**, on which the mirror is deposited. Lowering the micromirror brings the micromirror closer to the torsion hinge axis and reduces the moment of inertia during the deflection of the micromirror. A lower moment of inertia leads to a shorter switching time between digital states, which is desirable in achieving the greatest number of gray levels.

A shorter mirror support spacervia **326** also provides less opportunity for light to get under the mirrors when the mirrors are tilted. Light that does get under the mirrors is scattered by the micromirror superstructure. Some of the light scattered by the micromirror superstructure eventually passes between the mirrors, enters the aperture of the projection lens, and reaches the image plane where it lowers the contrast ratio of the display system.

The shorter mirror support spacervia **326** also reduces the torque experienced by the mirror support spacervia **326**. Additionally, for a given hole width, the use of a thinner second spacer layer **702** increases the metal step coverage on the sides of the spacervia hole. Because of the improved step coverage and reduced torque, the mirror support spacervia **326** can have a smaller width. A narrow mirror support spacervia **326** reduces the size of the hole in mirror **704**, increasing the optically active mirror area and reducing the amount of light scattered by the hole in the mirror. As a result, both the efficiency and the contrast ratio of the display system are increased.

Unfortunately, the large gaps between the torsion hinge yokes **114** and torsion hinge caps **122** coupled with the thinner second spacer layer **702** shown in FIG. **7**, make it much more difficult to deposit a planar second spacer layer **702**. An additional spacer layer is used to enable the second spacer layer **702** to create a planar surface on which to deposit the mirror metal layer. This additional spacer layer preferably is the combined thickness of the torsion hinge metal layer **604**, the second metal layer **608**, and any trench etched into the first spacer layer **602** when the torsion hinge **604** and torsion hinge yoke **608** layers and etch stops **606** are etched and removed. The second spacer layer **702** is patterned to form inverse yoke regions **802**, shown in FIG. **8**. The inverse yoke regions **802** shown in FIG. **8** are merely one example of shapes that provide a suitable surface on which to deposit a planarizing spacer layer **702**.

After the additional spacer layer has been patterned to form inverse yoke regions **802** and deep UV hardened, the second spacer layer **702** is deposited as shown in FIG. **7**. The second spacer layer is typically a 1.3 μm thick layer of positive photoresist which is patterned to create a form in which a mirror support spacervia **326** is deposited. After the second spacer layer has been deposited and patterned, a mirror metal layer **704** is deposited and patterned to form the mirrors. The mirror metal layer **704** is typically a 3000 Å thick layer of an aluminum alloy. Once the mirror metal layer **704** is patterned, the first and second spacer layers, as well as the inverse yoke layer are etched away, allowing the completed micromirror superstructure to deflect about the axis of the torsion hinge **120**.

The micromirror architecture described above provides many advantages over prior architectures. A primary advantage is a large increase in fabrication yield. This higher yield is also locked-in: micromirror superstructure fabrication processes will not create faults in earlier layers since the dielectric isolation layer physically blocks access to the earlier layers. This physical barrier also simplifies failure analysis since one fault will not start a chain reaction of secondary faults.

The new architecture is much more tolerant of debris than prior designs. Conductive debris cannot cause short circuits since the only exposed structures are all operating at the mirror bias/reset voltage. Debris is much less likely to cause mechanical obstructions since the new architecture provides larger gaps between the deflectable rigid structure and the stationary support structure.

One potentially negative side-effect of the new architecture is the potential for the dielectric isolation layer to develop a surface charge. A surface charge is generated when ionizing radiation passes through the air gap beneath each mirror. The ionizing radiation, which may be cosmic rays or alpha particles from the package, strikes the air gap between the mirror and the address electrodes creating positive ions and electrons which are separated by the voltage field used to address the mirror. During periods in which the position of the mirror is held constant this resulting charge may become large enough to significantly reduce the applied electric field and interfere with the ability of the address electrodes to tilt the mirror reliably. Two solutions exist that prevent the dielectric isolation layer from charging. The first solution is to periodically reverse the sign of the applied electrostatic field across the air gap.

This technique, often called AC addressing, switches the polarity of the image data stored in a memory cell used to drive the address electrodes, and also the polarity of the mirror bias and reset voltage. This technique is often used in liquid crystal displays to prevent the migration of ionic contaminants through the liquid. Changing the polarity of the image data changes an address electrode voltage from logic high to logic low, and vice versa. If the polarity of the mirror bias voltage is reversed at the same time, the mirror will rotate the same direction as it did before the address and bias voltages were altered. The duration of each polarity

must be short enough to prevent significant surface charges from building up. Typically the polarity is reversed each frame.

A second solution to the surface charge problem also prevents a surface charge from forming. The surface charge is formed when gas inside the package chamber, typically nitrogen, is ionized. When ionized, nitrogen creates an electron and a positively charged nitrogen molecule. Since the electron has such a low mass, it is accelerated toward the dielectric layer by the voltage field and often reaches the dielectric layer before it recombines. Filling the micromirror device package with a gas having a large dissociative electron capture cross section, such as SF_6, results in ionization products which typically recombine before reaching the dielectric layer.

FIG. 9 is a schematic view of an image projection system **900** using an improved micromirror **902** according to the present invention. In FIG. 9, light from light source **904** is focused on the improved micromirror **902** by lens **906**. Although shown as a single lens, lens **906** is typically a group of lenses and mirrors which together focus and direct light from the light source **904** onto the surface of the micromirror device **902**. Image data and control signals from controller **914** cause some mirrors to rotate to an on position and others to rotate to an off position. Mirrors on the micromirror device that are rotated to an off position reflect light to a light trap **908** while mirrors rotated to an on position reflect light to projection lens **910**, which is shown as a single lens for simplicity. Projection lens **910** focuses the light modulated by the micromirror device **902** onto an image plane or screen **912**.

Thus, although there has been disclosed to this point a particular embodiment for an improved micromirror and process of manufacture thereof, it is not intended that such specific references be considered as limitations upon the scope of this invention except insofar as set forth in the following claims. Furthermore, having described the invention in connection with certain specific embodiments thereof, it is to be understood that further modifications may now suggest themselves to those skilled in the art, it is intended to cover all such modifications as fall within the scope of the appended claims.

What is claimed is:

1. A micromirror device comprising:

a substrate;

at least one address electrode supported by said substrate;

a mirror bias/reset conductor supported by said substrate;

a dielectric layer overlying said at least one address electrode;

a deformable element supported over said dielectric layer; and

a deflectable rigid member supported by said deformable element, wherein a voltage differential between said at least one address electrode and said rigid member is operable to create an electrostatic attraction between said at least one address electrode and said rigid member and to cause said deflectable rigid member to deflect toward said at least one address electrode.

2. The micromirror device of claim **1**, wherein said rigid member is a hinge yoke.

3. The micromirror device of claim **1**, wherein said rigid member is a mirror.

4. The micromirror device of claim **1**, wherein said deformable element is a torsion hinge.

5. The micromirror device of claim **1**, wherein said deformable element is a cantilever hinge.

6. The micromirror device of claim **1**, said dielectric layer further overlying said mirror bias/reset conductor.

7. The micromirror device of claim **1**, said dielectric layer further overlying said mirror bias/reset conductor, wherein portions of said dielectric layer are removed to allow said deflectable rigid member to contact said mirror bias/reset conductor.

8. A method of forming a micromirror device, said method comprising the steps of:

forming a mirror bias/reset conductor and address electrodes on a substrate;

forming a dielectric layer over said address electrodes; and

forming a deflectable rigid member supported by said substrate.

9. The method of claim **8**, wherein said step of forming a deflectable rigid member comprises the step of forming a mirror.

10. The method of claim **8**, wherein said step of forming a deflectable rigid member comprises the step of forming a hinge yoke.

11. The method of claim **8**, wherein said step of forming a deflectable rigid member comprises the step of forming a mirror and a torsion hinge yoke.

12. The method of claim **8**, wherein said step of forming a dielectric layer over said address electrodes comprises forming a dielectric layer over said address electrodes and said mirror bias/reset conductor.

13. The method of claim **8**, further comprising the step of forming a deformable member supported by said substrate, said deflectable rigid member connected to and supported by said deformable member.

14. The method of claim **13**, wherein said step of forming a deformable member comprises the step of forming a torsion hinge.

15. The method of claim **13**, wherein said step of forming a deformable member comprises the step of forming a cantilever hinge.

16. The method of claim **8**, further comprising the steps of:

depositing a spacer layer over said address electrodes and said mirror bias/reset conductor;

opening vias in said spacer layer;

depositing a metal in said vias; and

patterning said metal to form at least one support structure, said at least one support structure supporting said deflectable rigid member above said substrate.

17. The method of claim **16**, further comprising the step of:

removing at least part of said spacer layer.

18. A method of forming a micromirror device, said method comprising the steps of:

forming a mirror bias/reset conductor and address electrodes on a substrate;

forming a dielectric layer over said address electrodes; and

forming a deflectable rigid member supported by said substrate by:

depositing a first spacer layer;

depositing at least one metal layer on said first spacer layer;

patterning said at least one metal layer to form said support structures, a deformable element, and a hinge yoke;

forming a second spacer layer over portions of said first spacer layer not covered by said support structures, said deformable element, and said hinge yoke;

depositing a third spacer layer over said second spacer layer, said support structures, said deformable element, and said hinge yoke;

opening vias through said third spacer layer to said hinge yoke; and

forming micromirrors on said third spacer layer.

19. The method of claim 18 wherein said step of forming a second spacer layer comprises the step of forming a second spacer layer over said deformable element.

20. The method of claim 18 wherein said step of depositing a third spacer layer comprises the step of depositing a planarizing third spacer layer.

21. A micromirror device comprising:

a substrate;

a first layer supported by said substrate;

a second layer spaced apart from said first layer, said second layer forming a micromirror; and

a third layer disposed between and spaced apart from said first layer and said second layer, said third layer supported by said substrate and supporting said second layer, said third layer comprising at least one deformable element and at least one hinge yoke, wherein address electrodes are formed only in said first layer.

22. The micromirror device of claim 21 further comprising a dielectric layer disposed on said address electrodes.

23. A method of forming a micromirror device, said method comprising the steps of:

forming a mirror bias/reset conductor and address electrodes on a substrate;

forming a dielectric layer over said address electrodes;

forming a hinge yoke supported above said address electrodes; and

forming a micromirror supported by said hinge yoke.

24. The method of claim 23, further comprising the step of forming a dielectric layer over said address electrodes and said mirror bias/reset conductor.

25. The method of claim 23, further comprising the step of forming a deformable member supported by said substrate, said hinge yoke connected to and supported by said deformable member.

26. The method of claim 25, wherein said step of forming a deformable member comprises the step of forming a torsion hinge.

27. The method of claim 25, wherein said step of forming a deformable member comprises the step of forming a cantilever hinge.

28. The method of claim 23, further comprising the steps of:

depositing a spacer layer over said address electrodes and said mirror bias/reset conductor;

opening vias in said spacer layer;

depositing a metal in said vias; and

patterning said metal to form said at least one support structure, said at least one support structure supporting said micromirror above said substrate.

29. The method of claim 28, further comprising the step of:

removing at least part of said spacer layer.

30. The method of claim 23, said step of forming a micromirror comprising the steps of:

depositing an inverse spacer layer, said inverse spacer layer patterned to avoid said hinge yoke;

depositing a spacer layer over said inverse spacer layer and said hinge yoke;

opening vias through said spacer layer to said hinge yoke; and

forming micromirrors on said spacer layer.

* * * * *

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[54] **METHOD OF MAKING A SUPPORT POST FOR A MICROMECHANICAL DEVICE**

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[58] **Field of Search** 359/871, 872, 359/883, 295, 224, 291, 214, 292, 293

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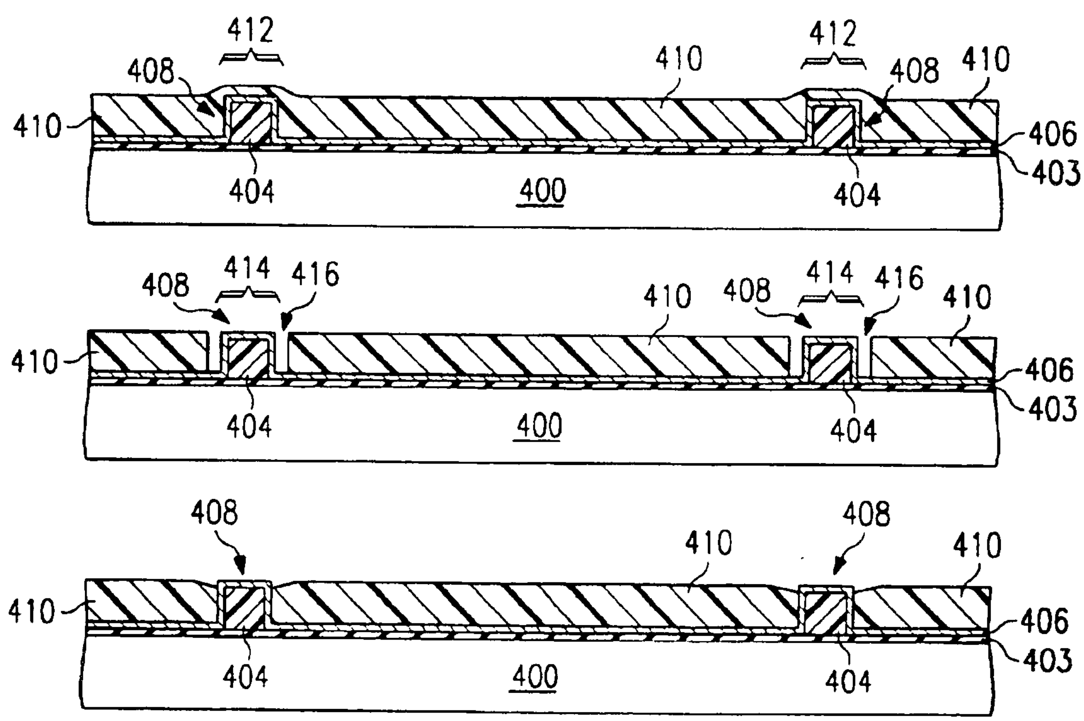
[57] **ABSTRACT**

A support pillar **426** for use with a micromechanical device, particularly a digital micromirror device, comprising a pillar material **422** supported by a substrate **400** and covered with a metal layer **406**. The support pillar **426** is fabricated by depositing a layer of pillar material on a substrate **400**, patterning the pillar layer to define a support pillar **426**, and depositing a metal layer **406** over the support pillar **426** enclosing the support pillar. A planar surface even with the top of the pillar may be created by applying a spacer layer **432** over the pillars **426**. After applying the spacer layer **432**, holes **434** are patterned into the spacer layer to remove any spacer material that is covering the pillars. The spacer layer is then reflowed to fill the holes and lower the surface of the spacer layer such that the surface is coplanar with the tops of the support pillars **426**.

24 Claims, 8 Drawing Sheets



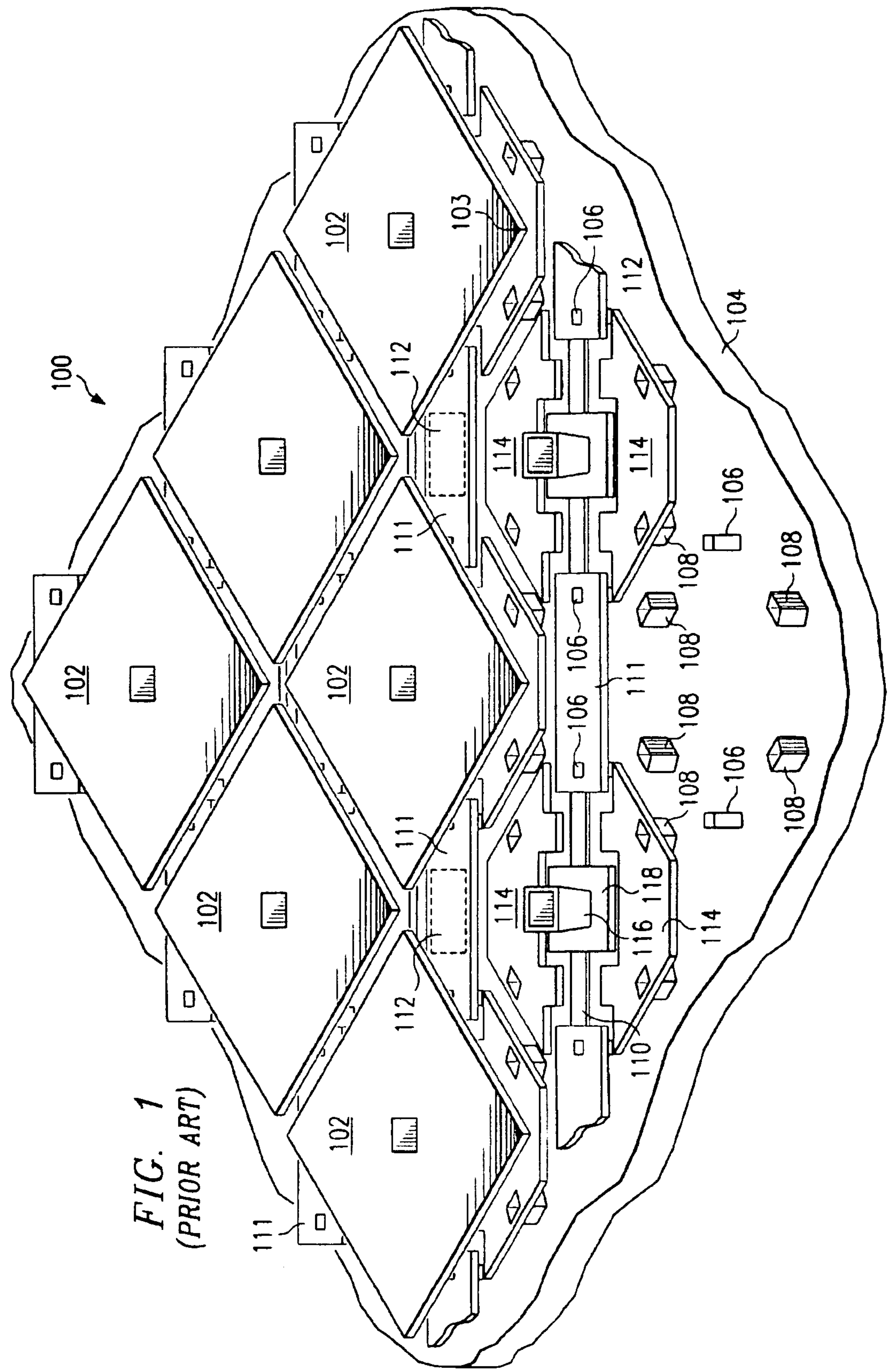


FIG. 1
(PRIOR ART)

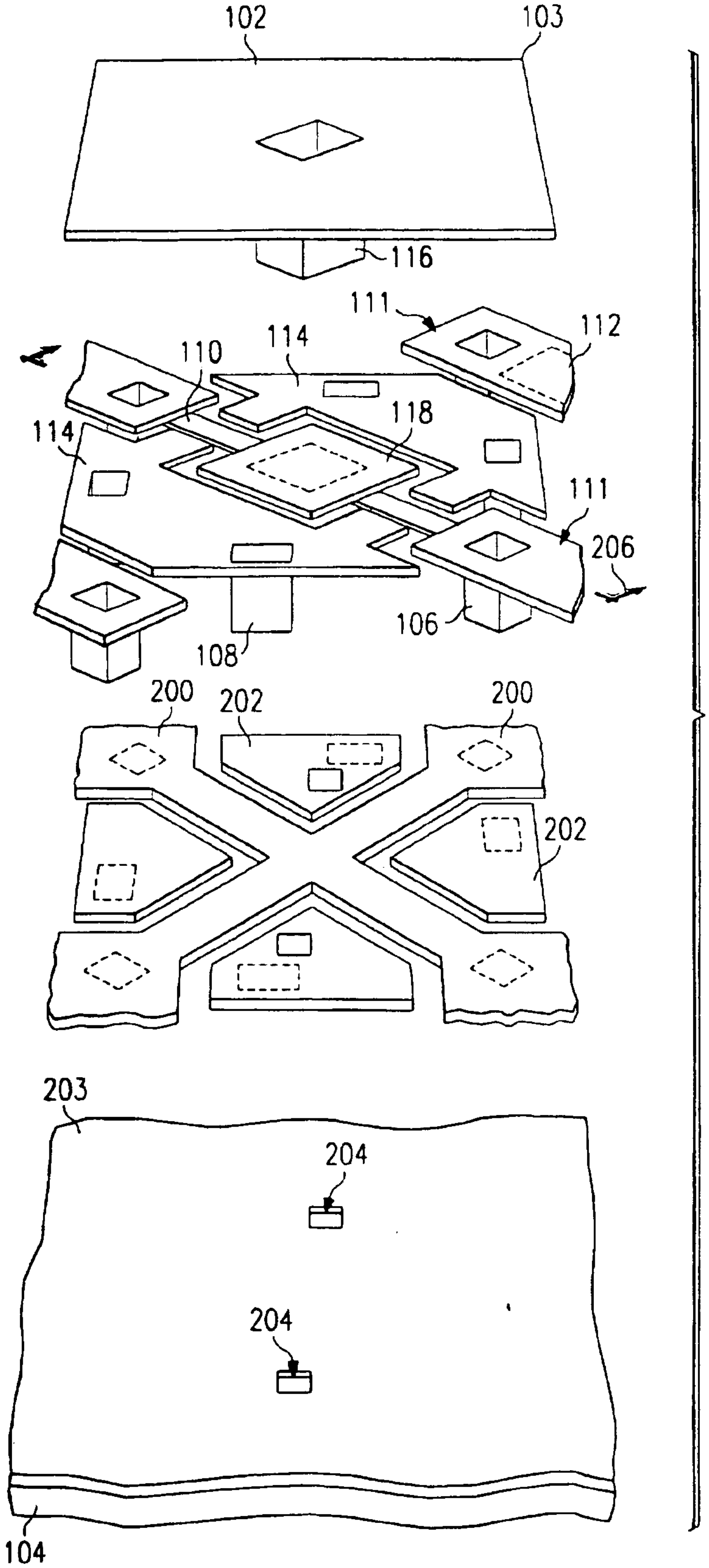


FIG. 2
(PRIOR ART)

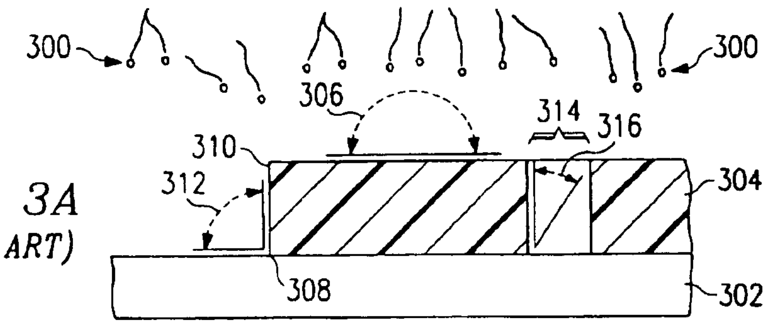


FIG. 3A
(PRIOR ART)

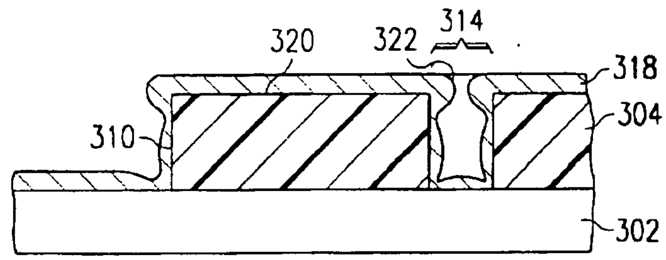


FIG. 3B
(PRIOR ART)

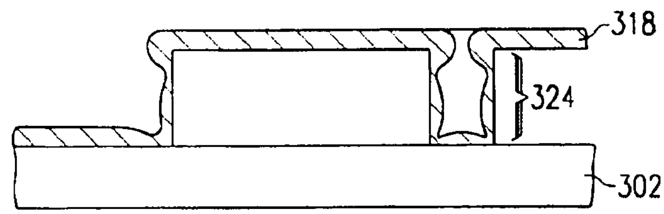


FIG. 3C
(PRIOR ART)

FIG. 4A

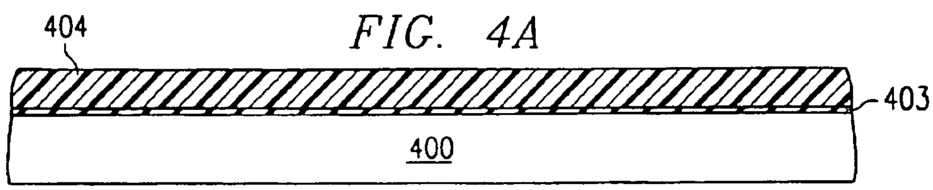


FIG. 4B

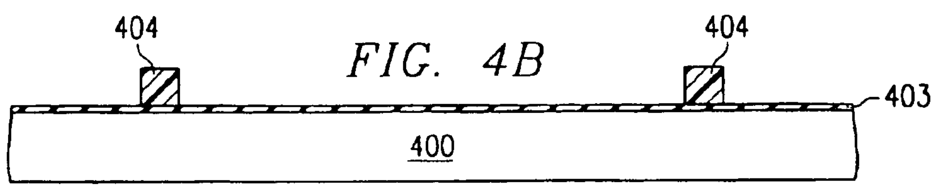


FIG. 4C

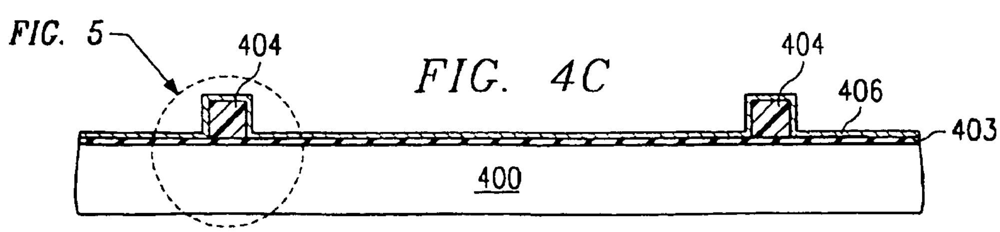


FIG. 4D

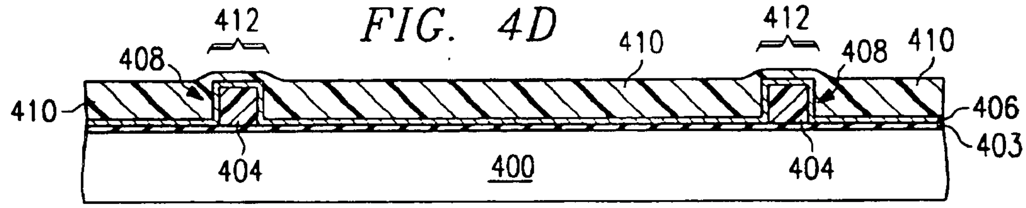


FIG. 4E

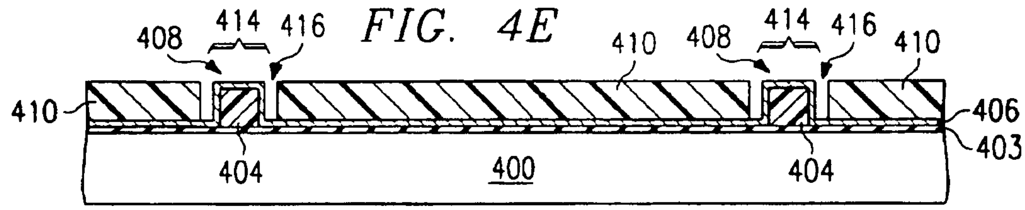


FIG. 4F

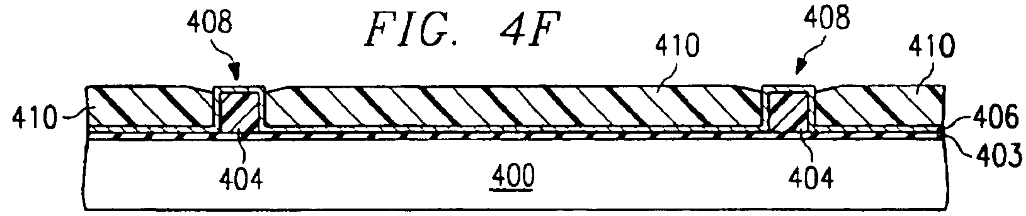


FIG. 4G

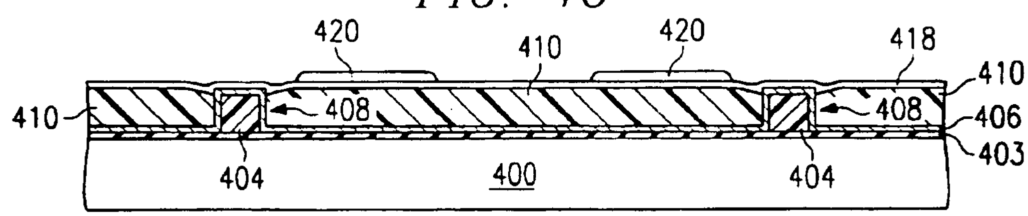


FIG. 4H

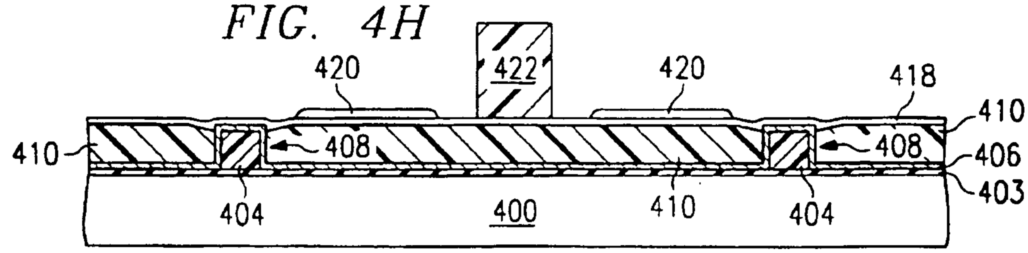


FIG. 4I

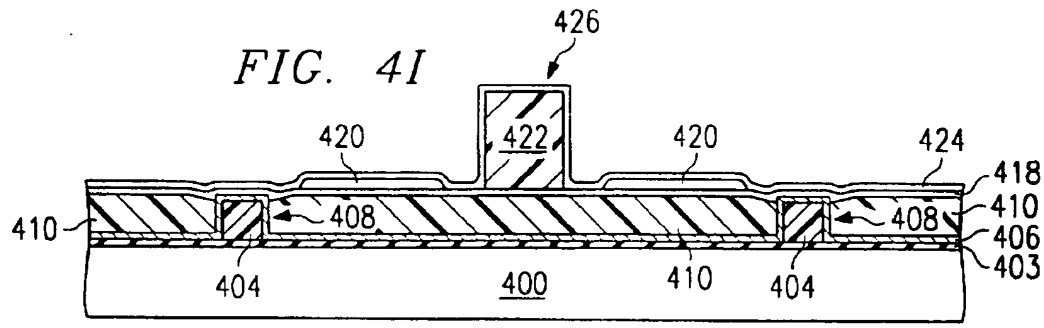


FIG. 4J

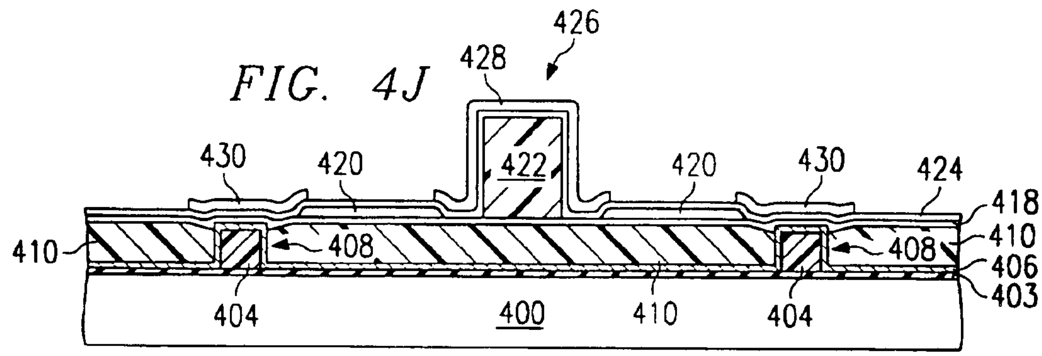


FIG. 4K

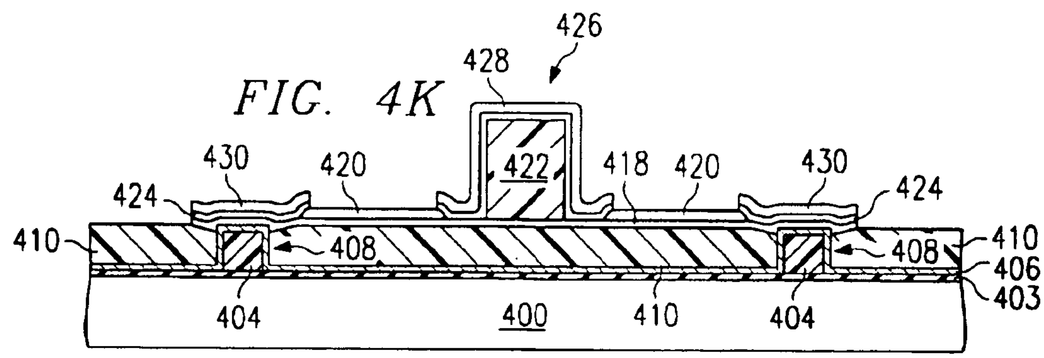


FIG. 4L

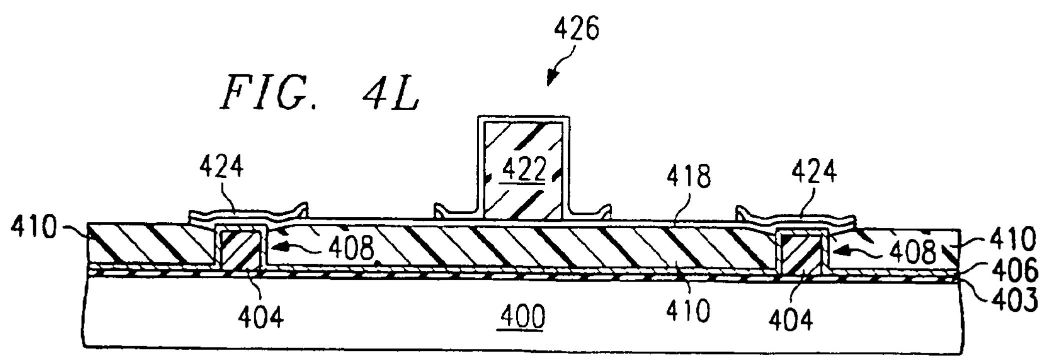


FIG. 4M

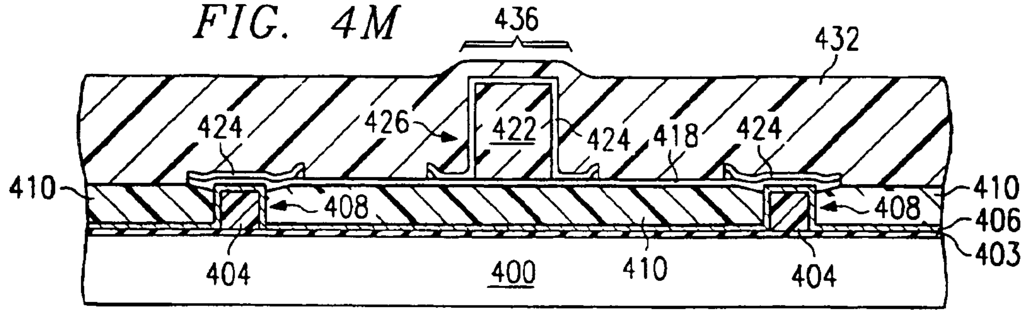


FIG. 4N

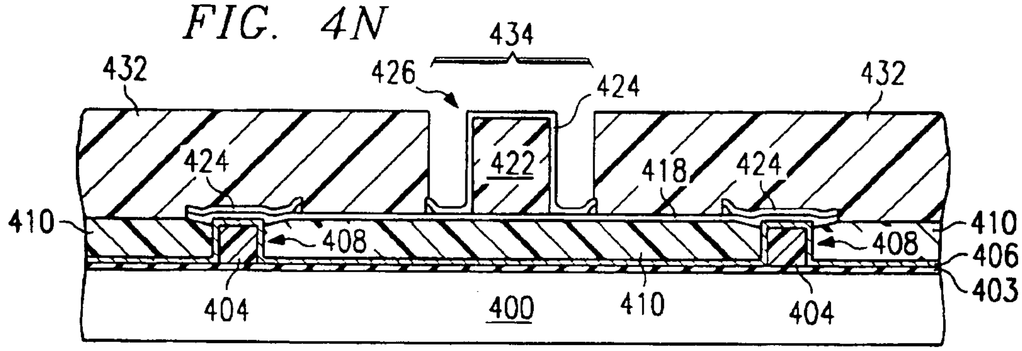


FIG. 4O

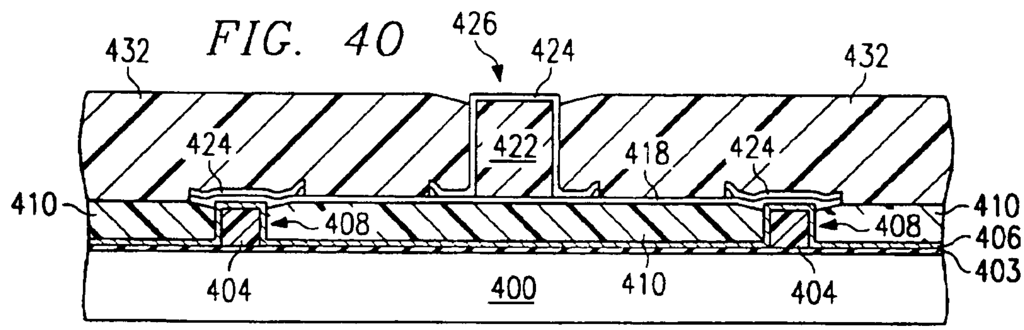


FIG. 4P

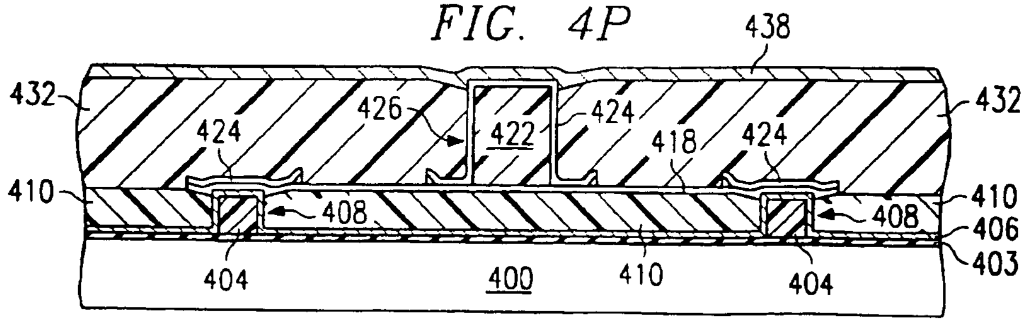


FIG. 4Q

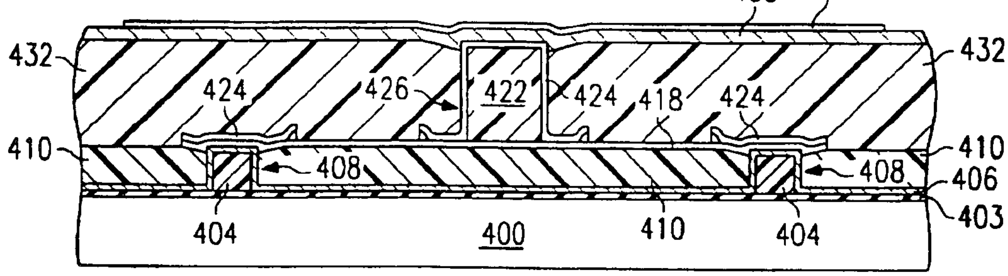


FIG. 4R

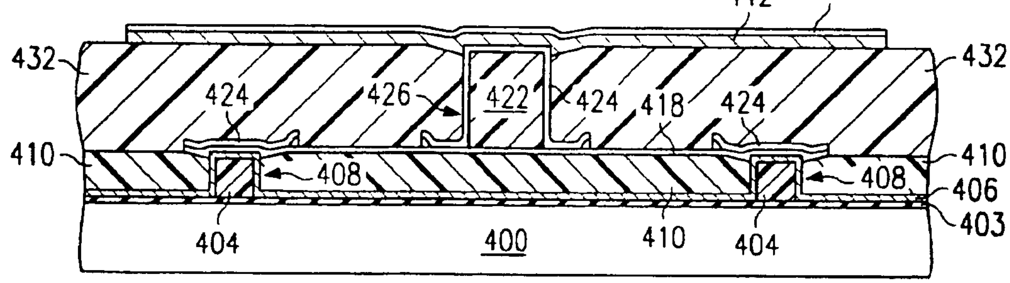


FIG. 4S

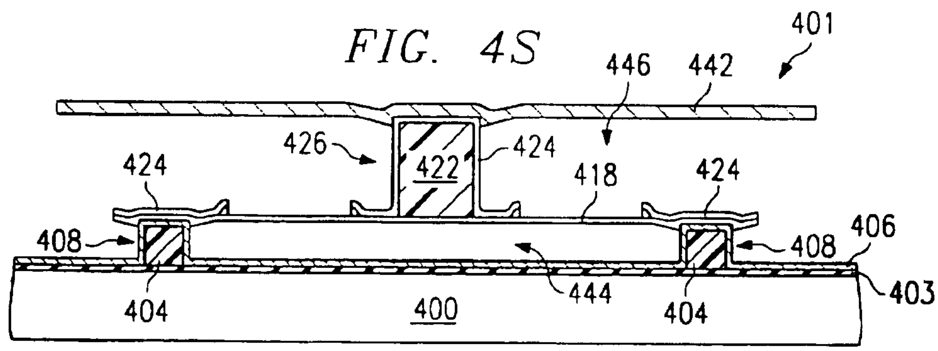
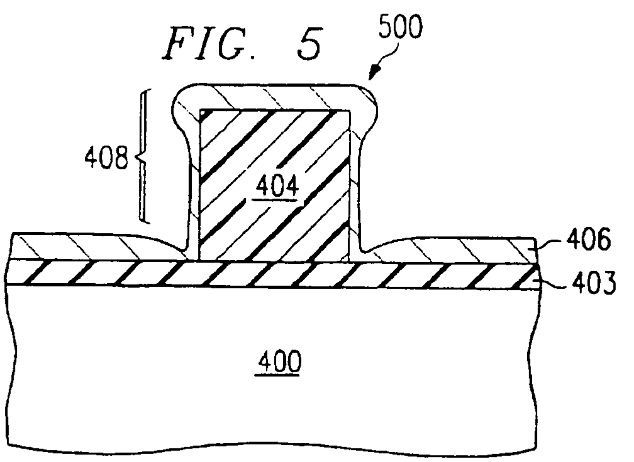


FIG. 5



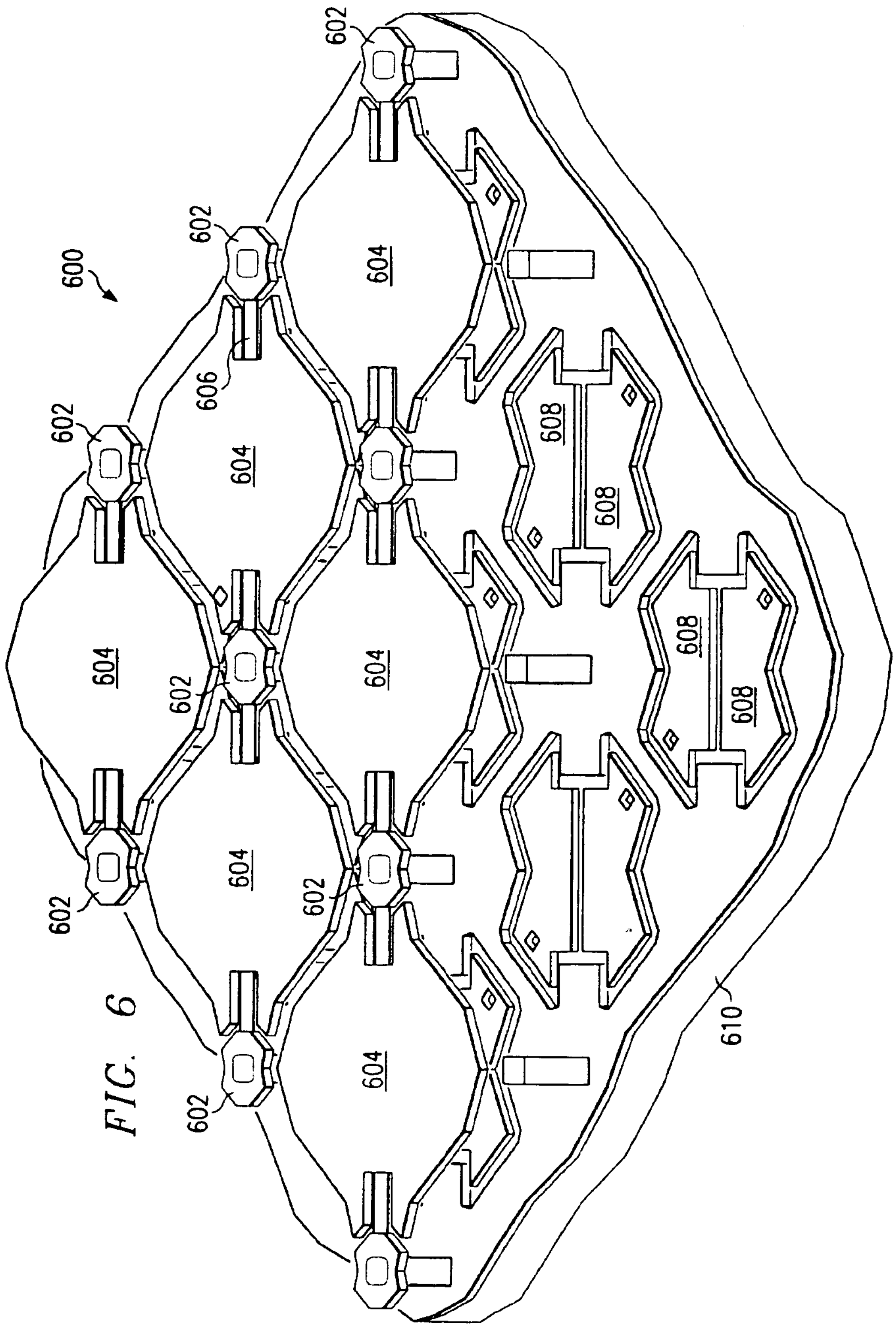


FIG. 6

METHOD OF MAKING A SUPPORT POST FOR A MICROMECHANICAL DEVICE

This is a divisional of application Ser. No. 08,333,186, filed Nov. 2, 1994 U.S. Pat. No. 5,650,881.

TECHNICAL FIELD OF THE INVENTION

This invention relates to micromechanical devices and more particularly to support structures integral to such devices.

BACKGROUND OF THE INVENTION

One type of light deflecting spatial light modulator (SLM) is the digital micromirror device (DMD). DMDs are available in several different forms including flexure beam, cantilever beam, and both conventional and hidden hinge torsion beam designs. Each type of DMD includes an array of small mirrors which move out of a resting position, e.g. rotate or deflect, in response to an electrostatic field produced by an electrical signal, typically called an address signal. The resting position of the mirror is typically parallel to the surface of the device. Light is reflected from the surface of the mirror and as the mirror is moved, the direction of the reflected light is changed. The resting position of the mirror is determined by a beam or spring, often called a hinge, which supports the mirror and which stores energy during mirror movement. This stored energy tends to return the mirror to the resting position when the address voltage is removed or reduced.

Deformable micromirror devices are also referred to as DMDs. The difference between digital micromirror devices and deformable micromirror devices is that digital micromirror devices are operated in a bistable mode, as taught in U.S. Pat. No. 5,061,049, issued Oct. 29, 1991, and entitled "Spatial Light Modulator and Method". Digital operation of the micromirror devices includes the application of a bias voltage that ensures that the mirrors have a maximum rotation in either the "on" or "off" direction regardless of the magnitude of the address voltage. The mirror deflection of deformable micromirror devices is an analog function of the voltage applied to the device. The structure of digital micromirror devices and deformable micromirror devices is very similar. The disclosed invention may be used in conjunction with either digital, or deformable micromirror devices.

DMDs are typically used in a dark field projection arrangement and can be used, for example, in HDTV applications where a large array of pixels is necessary for the desired image resolution. In addition to the high resolution capabilities of the DMD, another feature that is very useful in video display applications is the speed at which the mirror can be controlled, or the response time of the device. The short response time allows the present generation of DMDs to be toggled on and off up to 180 thousand times each second. Each deflection cycle stores energy in the DMD beam or spring and mechanically stresses the device structure.

DMDs are part of a larger group of devices known as micromechanical devices. Micromechanical devices include some accelerometers, flow sensors, electrical motors, and flow control devices. These devices are often fabricated by processes known as micromachining. Micromachining involves the removal of unwanted material from either the substrate on which the device is being fabricated, or from one or more layers of material that is deposited during the fabrication of the device. The material is typically removed to allow some part of the completed device to move. For

example, material must be removed from a motor to allow a rotor to spin around a stationary shaft. In the case of a DMD, material must be removed from below the DMD mirror to allow the mirror to deflect or rotate.

Sometimes an entire layer, called a sacrificial layer is used during the fabrication process. For example, DMDs are typically fabricated by depositing a sacrificial layer over the circuitry required to deflect the mirror. Mirrors and their hinges are then built on this spacer layer by depositing and patterning one or more metal layers. The metal layers are typically aluminum or an aluminum alloy and are patterned to define a mirror connected to at least one hinge cap by a hinge. In early forms of DMDs, the sacrificial layer was removed from beneath the mirrors and hinges, leaving a portion of the sacrificial layer to support the hinge caps. The mirrors were suspended by the hinges above the wells formed by removing the sacrificial material.

Recent DMD designs include a hole or via in the sacrificial layer at the location of each hinge cap prior to depositing the hinge metal. When the hinge metal is deposited on the sacrificial layer, it is also deposited on the walls of the via, creating a topless hollow post structure known as a spacervia. After the mirrors, hinges and hinge caps are patterned, all of the sacrificial layer is removed leaving only the spacervia to support the hinge caps away from the device substrate. Other types of DMDs, such as the so called "Hidden Hinge" torsion beam device as taught by U.S. Pat. No. 5,083,857, issued Jan. 28, 1992 and entitled "Multi-Level Deformable Mirror Device", use two or more sacrificial layers. The hidden hinge torsion beam DMD uses one set of spacervias to support the hinges above the device substrate and a second set of spacervias to support the mirror above the hinges.

The electrostatic forces used to deflect the mirrors generate mechanical stresses in the supporting hinge and spacervia structures. These stresses can lead to a failure in the supporting structure, ruining the device. There is a need in the art for an improved support structure for DMDs and other micromechanical devices.

SUMMARY OF THE INVENTION

The present invention provides a structure and process for an improved support post structure, called a support pillar. The support pillar may he used in a micromechanical device, particularly a digital micromirror device (DMD). The support pillar is fabricated by depositing a layer of pillar material on a substrate, patterning the pillar material to define the shape of the support pillar, and depositing a metal layer over the remaining pillar material thereby enclosing, the pillar material in a metal sheath. A planar surface, even with the top of the pillar, may be created by applying a spacer layer around the pillars. After applying the spacer layer, holes are patterned into the spacer layer to remove any pillar material that is covering the pillars. The spacer layer is then reflowed to fill the holes and lower the surface of the spacer layer such that the surface is coplanar with the tops of the support pillars.

The support pillar may be used as a support post in any type of digital micromirror device including the conventional torsion beam DMD and the hidden hinge DMD. Hidden hinge DMDs may be fabricated using the support pillar to support either the hinges, the address electrodes, or the mirror, or any combination thereof.

The disclosed support structure and method of fabricating the same have several advantages over existing designs including improved support structure strength, a less chemi-

cally reactive spacer surface on which to continue device fabrication, and better spacer surface planarization.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a perspective view of a portion of a typical hidden hinge torsion beam DMD array of the prior art.

FIG. 2 is an exploded perspective view of a hidden hinge torsion beam DMD element of the prior art.

FIG. 3A is a cross-sectional view of metal being sputtered onto a substrate and a layer of sacrificial material.

FIG. 3B is a cross-sectional view of the substrate of FIG. 3A after metal has been sputtered onto it.

FIG. 3C is a cross-sectional view of the substrate of FIG. 3A after metal has been sputtered onto it and the sacrificial material removed.

FIGS. 4A through 4S are cross-sectional views taken along the hinge axis of one element of a DMD array showing various stages in the fabrication of a DMD element having support posts according to one embodiment of the present invention.

FIG. 5 is a cross-sectional view showing the metal step coverage of the hinge support pillar of FIG. 4C.

FIG. 6 is a perspective view of a portion of a typical torsion beam DMD having improved support posts according to one embodiment of this invention.

DETAILED DESCRIPTION

A new fabrication process is needed to yield sufficiently strong and reliable support structures which may be used in DMDs and other types of micromechanical devices. To avoid confusion between existing support structures and the improved structure taught herein, support structures of the prior art will be referred to as spacervias, while the improved structures taught herein will be referred to as support pillars. Although the specific embodiments shown, in this disclosure will show only DMD structures, the methods and structures taught are applicable to many other micromechanical devices.

FIG. 1 shows a perspective view of a portion of a hidden hinge torsion beam DMD array 100 of the prior art. Hidden hinge devices rely on two levels of spacervias to hold a mirror 102 away from a substrate 104. The first spacervia level includes a hinge support spacervia 106, and an address electrode support spacervia 108. The hinge support spacervia supports each end of a torsion hinge 110, away from the device substrate 104. The torsion hinge 110 attaches to the top of the hinge support spacervia 106 via a thick metal hinge cap 111. The metal hinge cap 111 strengthens the connection between the thin metal torsion hinge 110 and the hinge support spacervia 106 by ensuring adequate metal to metal contact between the hinge metal and the spacervia metal. On each hinge cap 111, is a landing site 112 which stops the rotation of either of two adjacent mirrors 102 when the mirrors are rotated towards the landing site 112. The address support spacervia 108 is used to hold an address electrode 114 away from substrate 104. The address support spacervias 108 and the hinge support spacervias 106 are typically the same height.

The second spacervia level includes a mirror support spacervia 116 which holds the mirror 102 above the torsion hinges 110. The mirror support spacervia 116 is fabricated on a thickened portion of the torsion hinge 110 called a hinge yoke 118. Like the hinge cap 111, the hinge yoke 118 strengthens the connection between the thin metal torsion hinge 110 and the mirror support spacervia 116 by ensuring adequate metal to metal contact between the torsion hinge 110 and the mirror support spacervia 116. The height of the mirror support spacervia 116 may be varied to control the maximum angular rotation of the mirror 102.

FIG. 2 is an exploded view of a single hidden hinge torsion beam DMD element. In addition to the structures discussed in regard to FIG. 1, FIG. 2 shows a metal bias/reset bus 200 and metal pads 202 which are deposited on the surface of the substrate 104. The metal bias/reset bus 200 supports the hinge support spacervias 106 and the metal pads 202 support the address electrode support spacervias 108. The metal pads 202 are connected, through vias 204, in a protective oxide layer 203, to the addressing circuitry built into the surface of the substrate 104. The metal pads electrically connect the address electrode support spacervias 108 to the addressing circuity. The bias/reset bus 200 and the metal pads 202 are typically fabricated a. part of the third device metalization layer or M3. The first two metal layers, M1 and M2, are used to interconnect the address circuitry on the substrate.

Referring back to FIG. 1, each mirror 102 and its address electrodes 114 form the two plates of an air gap capacitor. If a sufficient voltage bias is applied between the address electrode 114 and its associated mirror 102, the resulting electrostatic force will cause the mirror 102 to deflect towards the address electrode 114 thereby twisting the torsion hinge 110. If the applied voltage is sufficiently large, the mirror 102 will deflect until the mirror tip 103 touches the associated landing site 112 on the hinge cap 111, stopping the mirror rotation. If the hinge cap 11 did not contact the mirror tip 103 and stop the rotation of the mirror 102, the mirror 102 would touch the address electrode 114 and short circuit the bias voltage. Because there is one address electrode 114 on each side of the hinge axis in each element, the mirror 102 may be rotated in either direction, allowing the mirror 102 to assume one of two fully deflected states.

When the bias voltage is removed from the mirror 102 and address electrodes 114, the energy stored by the deformation of the torsion hinge 110 will tend to return the mirror 102 to the undeflected or neutral state. However, short-range attractive forces between the mirror 102 and the landing site 112 often cause the mirror 102 to stick to the landing site 112. When this occurs, a technique known as resonant reset may be used to free the stuck mirrors 102. The resonant reset technique uses a voltage pulse, or series of pulses, to store mechanical energy in the mirror 102. Typically resonant reset is a series of five −24 volt pulses applied to the mirror 102 at the resonant frequency of the mirror 102, approximately 5 MHz. Each pulse creates a very strong attraction between the mirror 102 and the address electrode 114. Because the mirror tip 103 is held in place by the landing site 112, the center of the mirror 102 bends towards the substrate 104 and the upper surface of the mirror 102 becomes concave. When the pulse is removed, the attraction ceases and the mirror 102 springs upward, becoming convex. Subsequent pulses increase the mirror deformation thereby storing additional energy. By the time the final reset pulse is removed, the energy stored in the mirror 102 is sufficient to spring the mirror 102 away from the landing site 112, allowing the energy stored in the torsion hinge 110 to return the mirror 102 to the neutral position.

The electrostatic forces responsible for deforming the mirror **102** and the torsion hinges **110** also torque and flex the spacervias **106**, **108**, **116** which support portions of the device. The stresses involved can cause the spacervias **106**, **108**, **116** of prior art DMDs to break destroying the device. These failures usually occur via two failure modes. The first failure mode occurs when a spacervia **106**, **108**, **116** breaks at or near the point of attachment of the hinge cap **111**, address electrode **114**, or mirror **102**, that is supported by the top of the spacervia. The second primary failure mode occurs when a spacervia **106**, **116**, or **108** breaks at or near the point of attachment to the bias/reset bus **200** or hinge yoke **118** beneath the spacervia **106**, **108**, **116**. Failures of the spacervias **106**, **108**, **116** have been attributed to the poor metal coverage on the spacervia walls, or step coverage, obtained through the present fabrication processes. Usually the metal is too thin either at the base or near the top of the spacervia.

The address electrode support spacervias **108**, the hinge support spacervias **106**, and the mirror support spacervias **116** of the prior art are typically made by lining a hole, or via, in a sacrificial material with sputtered metal. When the sacrificial material is removed, the liner remains forming a spacervia. FIG. 3A depicts metal particles **300** being sputtered towards a substrate **302** that is partially covered by sacrificial material **304**. During the sputtering process, the metal **300** approaches the surface from all directions. Therefore, metal may reach a flat horizontal surface **320** from a 180° arc, as shown by region **306**.

Point **308** at the base of the wall structure **310** is shaded by the wall structure **310** and can only receive metal arriving at point **308** from a 90° arc, as shown by region **312**. Because point **308** can only receive metal from half the arc that a planar surface receives metal from, only about half as much metal will he deposited at point **308** compared to a planar area with no shading. The shading problem is even greater for the via **314**. Metal must approach the bottom corners of the via **314** almost vertically as shown by region **316**. Because more metal can reach the top portion of the walls compared to the bottom portion, an overhang will develop. The overhang further restricts metal from reaching the bottom of the wall, resulting in poor metal coverage of the lower portions of the wall.

FIG. 3B shows a metal layer **318** which has been sputtered onto the substrate **302** and spacer **304** of FIG. 3A. Metal layer **318** is thinner on the sides of a wall structure **310** than on a flat horizontal surface **320**. The metal layer **318** is especially thin on the bottom portion of the via **314**. A thin area also develops immediately below the top of the via **314**. This thin area is caused by overhang **322** which develops at the top of the via **314** as the metal layer **318** is being sputtered. FIG. 3C shows the substrate **302** and metal layer **318** after the sacrificial material **304** has been removed. This leaves a spacervia **324** that was formed in the via **314** through the sacrificial material **304**. The thin, weak areas of the metal layer **318** near both the top and bottom of the spacervia **324** are prone to failure when the spacervia **324** is stressed.

The higher the aspect ratio (i.e. ratio of the via height to via width), the worse the step coverage near the bottom of the via is likely to be. When fabricating a spacervia **324**, a thick metal layer must be deposited to ensure that adequate metal reaches the lower walls of the via **314**. Unfortunately, the metal thickness cannot be arbitrarily increased. As the metal is deposited, the overhang **322** grows faster than the thickness of the metal on the lower portions of the walls and will eventually seal off the via preventing any additional metal from entering the via **314**. Other constraints also limit the amount of metal that may be deposited into the via **314** during the typical MD fabrication steps. For example, during the fabrication of a typical hidden hinge DMD of the prior art, the mirror support spacervia **116** and the mirror **102** are formed during the same metal deposition step. Depositing too much metal will thicken the mirror **102** which reduces the mirror specularity and requires a higher resonant reset frequency. Reset efficiency drops off markedly with increasing reset frequency, because of frequency dependent damping effects. Also, increasing the mirror thickness lengthens the response time of the mirror **102** by increasing the mirror moment of inertia.

There are at least three improvements to spacervias **324** that may increase their strength. First, the size of a spacervia **324** could be enlarged to allow better metal coverage of the sides of the spacervia **324**. However, because the mirror support spacervia **116** has an open top which reduces the active area of the DMD mirror **102**, enlarging the mirror support spacervia **116** results in an unacceptable loss in mirror active area. Enlarged address support spacervias **108** also reduce the usable size of address electrodes **114**, thereby reducing the electrostatic force generated between the address electrode **114** and the mirror **102**. A second approach involves changing the profile of the spacervia **324** to avoid reentrant spacervia contours. Reentrant contours occur when the via **314** used to form the spacervia **324** widens after entering the sacrificial material in which the via **314** is formed. A spacervia with a reentrant contour is similar to the overhang discussed above. The overhang causes the reentrant contour spacervia to have poor metal step coverage near the top of the spacervia **324** and may allow the hinge cap **111** or mirror **102** to break away from the spacervia **324**. Another solution is to grow an oxide liner on the inside of the spacervia **324** after the metal is deposited. The oxide liner is grown on the inside of the spacervia **324** at the base of the spacervia **324** to give it increased mechanical strength where the metal thickness is insufficient. Although these improvement: increase the strength of spacervias **324**, they have not yet yielded a sufficiently strong, reliable spacervia **324** for DMDs.

A new architecture and process, called the Reflow Inverse Spacervia Pillar (RISP) process, has been invented to address the mechanical weaknesses of the spacervia design. It replaces the photoresist vias of the prior designs with photoresist pillars. Because the pillars are relatively far apart, the base of the pillars is not shaded to the extent that the base of a via is shaded during the sputtering process. The step coverage of a pillar is much better than the step coverage of a hole or trench having the same aspect ratio. Therefore, a support pillar with a RISP architecture has much better strength than a spacervia **324** of the prior art.

FIGS. 4A through 4S show a cross-sectional view of a DMD element **401**, according to one embodiment of the present invention, during the various stages of its fabrication. The cross-sectional views are taken along the hinge axis as shown by **206** in FIG. 2. FIG. 4A shows a substrate wafer **400**, typically silicon, on which addressing circuitry and the first two metalization layers previously have been fabricated. The second metal layer is covered with a protective oxide layer **403**. Vias **204**, shown in FIG. 2, are opened in the oxide layer **403** to allow the metal pads **202** to contact the addressing circuitry fabricated on the substrate **400**. Although not shown in FIG. 4A, a thin metal layer is typically deposited over the protective oxide layer **403**. This thin metal layer, which is typically tungsten or aluminum, establishes electrical contact with the addressing circuitry on

the substrate 400 and may act as an etch stop during subsequent etch steps.

A first layer of pillar material 404 typically a positive organic photoresist layer approximately 1.0 μm thick, is applied to the substrate 400. The layer of pillar material 404 is patterned and developed to leave portions of pillar material 404, as shown in FIG. 4B, which will form an integral part of the hinge support pillars. Portions of the layer of pillar material 402 also will form address electrode support pillars. However, the address electrode support pillars are not shown in the cross section of FIGS. 4A–4S. After the portions of pillar material 404 have been formed, they may be deep UV hardened to a temperature of approximately 220° C. to prevent them from melting or bubbling during the remaining processing steps.

Other materials may be used instead of photoresist for the layer of pillar material 404 Alternate materials are typically dielectrics such as polysilicon, oxide, nitride, or oxynitride. When a dielectric is used, the thin metal layer deposited over the protective oxide layer 403, and into the vias 204, may be used as an etch stop, facilitating complete removal of the pillar material 404 from the vias 204. Although other materials may be used for the pillar material layer 404, photoresist is preferred because most alternate materials require separate patterning and etching steps. For example, a 1 μm thick silicon dioxide layer is grown on the substrate wafer 400 and covered with a layer of photoresist. The photoresist is patterned and developed to protect the portions of the silicon dioxide layer that are to form the support pillars. The silicon dioxide layer is then etched leaving only the desired portions of pillar material 404.

After patterning the layer of pillar material 404, the substrate 400 and the remaining portions of pillar material 404 are covered with a layer of metal 406, as shown in FIG. 4C. The metal layer, typically aluminum or an aluminum alloy, which forms the third metalization layer, M3, is typically sputtered onto the substrate to a thickness of 4000 Angstroms. The M3 metalization layer is patterned to form the bias/reset bus 200 and metal pads 202 that were shown in FIG. 2. Because the sectional views in FIGS. 4A–4S are taken along the hinge axis, the bias/reset bus appears as a continuous layer and the results of patterning the M3 layer are not shown. The completed hinge support pillar 408 is comprised of the remaining portions of pillar material 404 and a sheath of the M3 metal layer 406 which forms the bias/reset bus.

FIG. 5 is a cross-sectional view of one portion of a partially fabricated DMD 500 following the deposition of the M3 metal layer 406 showing the step coverage of a metalized hinge support pillar 408 from FIG. 4C. The pillar material 404 is encased in a metal sheath which is thinner on the sides than on the top. As discussed above in regard to FIG. 3, the reduction in metal on the sidewalls compared to metal on the top is due to the partial shading of the pillar material 404. Although the sidewalls receive less metal than the top of the pillar material 404, the remaining portions of pillar material 404 are spaced far enough apart to allow the sidewalls to receive metal from a wider arc, region 312 of FIG. 3A, than the spacervias of the prior art. Therefore, the sidewalls receive more metal, and more uniform coverage than the prior art spacervias. The improved metal coverage, combined with the composite nature of the metalized support pillar 408 results in a much stronger support pillar that does not exhibit a tendency to break away from either the hinge cap or the substrate.

Referring to FIG. 4D, a first spacer layer, called the hinge spacer layer 410, is then spun-on the substrate over the hinge

support pillars 408. The hinge spacer layer 410 is typically about 1.0 μm thick and, like all other photoresist layers used in this process, is typically a positive photoresist. As shown in FIG. 4D, the hinge spacer layer 410 will have a bump 412 above each pillar 408. The bumps 412 are caused by the process of spinning on the photoresist and are not desirable. If less photoresist is used to form hinge spacer layer 410 the bumps could be avoided but there may be significant undulations in the surface of the photoresist caused by the 'shadow' of the pillar as the photoresist flows around the pillar. The viscosity of the photoresist, which is a function of temperature, the spin-rate of the substrate wafer 400, and the thickness of the spacer layer all effect the surface of the finished layer. Under some conditions, it may be advantageous to deposit multiple thin layers rather than one thick layer. The ideal spacer layer would be perfectly planar and extend from the substrate wafer 400 to the top of the pillar 408, leaving a perfectly planar surface on which to continue fabricating the device.

The bumps 412 formed above each pillar 408 may be removed in a two-step process, shown in FIGS. 4E and 4F. First, the hinge spacer layer is patterned and developed to form oversized holes 414 through the spacer layer around each pillar 408. This step removes the spacer material that formed the bump 412 on top of each pillar 408. The hinge spacer layer 410 is then exposed to reduce its flow resistance and reflowed, typically by baking on a hot-plate, to fill in the space 416 around each pillar 408. Typically, the surface of the spacer layer 4110 is above the tops of the pillars 408 prior to the reflow operation. If the size of the oversized holes 414 has been chosen properly, the material above-the pillars 408 flows into the space 416 around each pillar 408 and the reflowed surface height is equal to the pillar height. In addition to filling in the space 416 around the pillars, the reflow process also improves the planarization of the spacer layer 410, and densifies the spacer material.

Planarization of the hinge spacer layer 410 is important in order to ensure consistent hinge strength and integrity. Also, any non-planar features on one device layer will ripple through the fabrication process and affect subsequent layers. Increasing the density of the spacer layer material has the process advantage of improving the resistance of the layer to future etch steps. After being reflowed, the hinge spacer layer 410 is typically deep UV hardened to a temperature of approximately 200° C. to prevent flow and bubbling during subsequent processing steps.

The hinge layer 418, as shown in FIG. 4G, is typically formed by sputter deposition of a thin aluminum alloy onto hinge spacer layer 410. The hinge layer 418 is typically 600 Angstroms thick and consists of 0.2% Ti, 1% Si and the remainder Al. According to the buried hinge fabrication process, as taught by U.S. Pat. No. 5,061,049, an oxide layer is deposited, typically by plasma deposition, over the hinge layer 418 and patterned in the shape of the torsion hinges to form oxide etch stops 420.

A second level of pillars is built over the hinge metal layer 418 to form the mirror support pillar. The mirror support pillar is fabricated by the same process used to fabricate the hinge and address electrode support pillars. A second layer of pillar material is deposited onto the substrate wafer, and patterned to leave portions of pillar material 422 as shown in FIG. 4H. The second layer of pillar material is typically a 2.2 μm thick layer of photoresist which is deep UV hardened to 180° C. to prevent flow and bubbling during subsequent processing steps. No degradation of the hinge spacer layer 410 or the hinge support pillar material 404 occurs because the first two layers of photoresist were hardened to higher temperatures (200° and 220° C.).

Next, as shown in FIG. 4I, a thick layer of electrode metal 424 is deposited over the first hinge metal layer 418 and the remaining portions of the second layer of pillar material 422. The electrode metal layer 424 is typically 3750 Angstroms thick is sputter deposited to form the mirror support pillar, hinge cap, and address electrodes. Although not shown in FIG. 4I, the electrode metal layer 424 is much thicker than the hinge metal layer 418. As the electrodes are being deposited, the pillar material 422 is encapsulated by the electrode metal forming the mirror support pillar 426 comprised of the pillar material 422 and a sheath of electrode metal 424. After the electrode metal 424 is deposited, an oxide layer is deposited and patterned as shown in FIG. 4J to form a mirror support pillar etch stop 428, a hinge cap etch stop 430, and an address electrode etch stop (not shown). The mirror support pillar etch stop 428 is patterned to protect both the mirror support pillar and the hinge yoke from the subsequent etch step.

After patterning the etch stops, the electrode metal layer 424 and the hinge metal layer 418 are both etched, leaving only the portions of the metal layers protected by the etch stops as shown in FIG. 4K. The etch stops are then stripped off as shown in FIG. 4L.

A second photoresist spacer layer, called the mirror spacer layer 432 is then spun onto the wafer, see FIG. 4M, and patterned with oversized holes 434 as shown in FIG. 4N to remove photoresist bump 436 and expose the mirror support pillar 426. The spacer is then baked until it is planarized as shown in FIG. 4O. Once again, as the spacer layer 432 reflows,, it becomes denser and fills the hole 434 around the mirror support pillar 426 but does not cover the top of the pillar 426.

A mirror metal layer 438 is deposited onto the second spacer layer 432 and the top of the support pillar 426. Typically the mirror metal layer is sputter deposited 4250 Angstroms thick. Another oxide layer is plasma-deposited and patterned to form a mirror etch stop 440 as shown in FIG. 4Q. The mirror metal layer 438 is then plasma etched to form the mirror 442, as shown in FIG. 4R.

Wafer level processing is now complete. The device must still be undercut by removing the remaining mirror spacer 432 and hinge spacer layers 410 and stripping the mirror oxide etch stop 440 from the mirror 442. Because the mirrors 442 are very fragile after the mirror spacer layer 432 is removed, the devices are typically sawn apart before undercutting the devices. However, this constraint is not a result of the disclosed process but rather a limitation due to existing methods of wafer separation. When wafer separation processes that do not create damaging debris or require damaging cleanup steps become available, the process steps may be reordered to allow the devices to be completed before the wafer is separated.

The mirror etch stop 440 is left in place during wafer separation to protect the mirror surface. The wafers are coated with PMMA, sawn into chip arrays and pulse spin-cleaned with chlorobenzene. After wafer separation, the chips are placed in a plasma etching chamber where mirror etch stop 440 and both spacer layers 432 and 410 are completely removed leaving air gaps 444 and 446 under the hinges and mirrors as shown in FIG. 4S. It is possible to leave portions of the spacer layers 432 and 410 as long as there is a sufficient air gap to allow the hinge to deform and the mirror to deflect.

Because the thermal coefficient of expansion of the encapsulated pillar material nearly matches the thermal coefficient of expansion of the aluminum pillar sheath, the encapsulated

material may be left inside the support pillars. If the difference between the thermal coefficient of expansion of the encapsulated material and the thermal coefficient of expansion of the aluminum pillar sheath is too great, the support pillar may break when exposed to high or low temperatures. To prevent damage to the support pillar caused by a mismatch in thermal expansion coefficients: a hole could be patterned in either the electrode or hinge metal layers to allow the encapsulated material to be removed by plasma etching.

Although the RISP process has been taught thus far only in terms of the hidden hinge DMD, many other devices could make use of the process. A conventional torsion beam DMD 600, shown in FIG. 6, consists of a mirror 604 supported by two torsion hinges 606 over address electrodes 608 fabricated on a semiconductor substrate 610. The RISP process could be used to form the hinge support pillars 602 which support the hinges 606 away from the substrate 610. Other micromechanical devices such as accelerometers, flow sensors, temperature sensors, and motors could also use the RISP process. The disclosed RISP process has several advantages over the conventional processes used to fabricate spacervias. As discussed earlier, the reflow process produces good planarization of the underlying electrode topography and also produces a spacer surface which is denser and less chemically reactive than in the prior art. These characteristics allow the spacer to better resist penetration by the aluminum etch byproducts during the mirror etch process, reducing the etch residues at the surface of the spacer. These etch residues can result in a thin surface film, or web, which may bridge between two mechanical elements, such as the mirrors 102 or hinge yokes 118, preventing the movement of the mirrors 102 and hinge yokes 118. Because there are minimal etch residues, no HF fume cleanup is required.

Thus, although there has been described to this point a particular embodiment for a support pillar and process, it is not intended that such specific references be considered as limitations upon the scope of this invention except insofar as set forth in the following claims. Furthermore, having described the invention in connection with certain specific embodiments thereof, it is to be understood that further modifications may now suggest themselves to those skilled in the art, it is intended to cover all such modifications as fall within the scope of the appended claims.

What is claimed is:

1. A method of fabricating a metalized support pillar comprising steps of:

depositing a pillar material on a substrate;

patterning said pillar material to define a support pillar;

depositing a metal layer over said support pillar wherein said support pillar is enclosed by said metal layer to form a metalized support pillar; depositing a spacer layer around said metalized support pillar;

removing a portion of said spacer layer around and on top of said metalized support pillar;

said removing step forming holes between said spacer layer and said metalized support pillar; and

reflowing remaining portion of said spacer layer to fill said holes between said second spacer layer and said metalized support pillar.

2. The method of claim 1 wherein said pillar material is an organic photoresist.

3. The method of claim 1 wherein said pillar material is a photoresist, said method further comprising the step of deep UV hardening said pillar material.

4. The method of claim 1 wherein said spacer layer is an organic photoresist.

5. The method of claim 1 wherein said depositing a pillar material step comprises spinning on a layer of an organic photoresist.

6. The method of claim 1 wherein said depositing a spacer layer step comprises spinning on a layer of an organic photoresist.

7. The method of claim 1 wherein said patterning step comprises partially removing said pillar material to leave said support pillar.

8. The method of claim 1 wherein said depositing a metal layer step comprises sputtering a metal layer over said support pillar.

9. The method of claim 1 wherein said depositing a metal layer step comprises sputtering an aluminum alloy over said support pillar.

10. The method of claim 1 wherein said reflowing step comprises heating said spacer layer.

11. A method of fabricating a micromirror device comprising steps of:

depositing a pillar material on a substrate;

patterning said pillar material to define at least one first support pillar;

depositing a first metal layer on said first support pillar to a form a first metalized support pillar;

depositing a first spacer layer on said substrate;

depositing a second metal layer over said first spacer layer and said first support pillar, said second metal layer forming at least one hinge;

depositing a second pillar material on said second metal layer;

patterning said second pillar material to define at least one second support pillar attached to said hinge;

depositing a third metal layer over said second support pillar to form a second metalized support pillar;

depositing a second spacer layer over said first spacer layer;

removing a portion of said second spacer layer from around and on top of said second metalized support pillar;

said removing step forming holes between said second spacer layer and said second metalized support pillar

reflowing remaining position of said second spacer layer to fill said holes between said second spacer layer and said second metalized support pillar;

depositing a fourth metal layer over said second spacer layer, said fourth metal layer forming as least one mirror attached to said second support pillar; and

removing said first spacer and said second spacer layer to form an air gap beneath said hinge and said mirror.

12. The method of claim 11 further comprising the steps of:

removing a portion of said first spacer layer from around and on top of said first metalized support pillar; and

reflowing said first spacer layer to fill any gap between said first spacer layer and said first metalized support pillar.

13. The method of claim 11 wherein at least one pillar material is a photoresist.

14. The method of claim 13 further comprising the step of deep UV hardening said photoresist pillar material.

15. The method of claim 11 wherein at least one spacer is a photoresist.

16. The method of claim 11 wherein said at least one spacer layer is deposited by spinning on a layer of an organic photoresist.

17. The method of claim 11 wherein at least one step of depositing a metal layer comprises the step of sputtering a metal layer.

18. The method of claim 11 wherein said at least one metal layer is an aluminum alloy layer.

19. A method of fabricating a micromirror device comprising steps of:

depositing and patterning a pillar material on a substrate to define at least one support pillar;

depositing a first metal layer on said support pillar to a form a metalized support pillar;

depositing a spacer layer on said substrate;

removing a portion of said spacer layer from on top of and around said metalized support pillar;

said removing step forming holes between said spacer layer and said metalized support pillar

reflowing remaining portion of said spacer layer to fill said holes between said second-spacer and said metalized support pillar;

depositing at least one additional metal layer over said spacer layer and said metalized support pillar, said at least one additional metal layer forming at least one hinge and at least one mirror suspended by said hinge from said support pillar;

removing portions of said spacer layer to form an air gap beneath said hinge and said mirror.

20. The method of claim 19 wherein said pillar material is a photoresist.

21. The method of claim 20 further comprising the step of deep UV hardening said photoresist pillar material.

22. The method of claim 19 wherein said spacer layer is a photoresist.

23. The method of claim 19 wherein said step of depositing a first metal layer comprises the step of sputtering a metal layer on said support pillar.

24. The method of claim 19 wherein said step of depositing a first metal layer comprises the step of sputtering an aluminum alloy on said support pillar.

* * * * *

US-PAT-NO: 5650881

DOCUMENT-IDENTIFIER: US 5650881 A

TITLE: Support post architecture for micromechanical devices

INVENTOR - INNM:

Hornbeck; Larry J.

US005535047A

United States Patent [19]
Hornbeck

[11] Patent Number: 5,535,047
[45] Date of Patent: Jul. 9, 1996

[54] ACTIVE YOKE HIDDEN HINGE DIGITAL MICROMIRROR DEVICE

[75] Inventor: Larry J. Hornbeck, Van Alstyne, Tex.

[73] Assignee: Texas Instruments Incorporated, Dallas, Tex.

[21] Appl. No.: 424,021

[22] Filed: Apr. 18, 1995

[51] Int. Cl.^{6} G02B 26/00
[52] U.S. Cl. 359/295; 359/224; 359/846
[58] Field of Search 359/219, 295, 359/292, 224, 214, 290, 230, 223, 846

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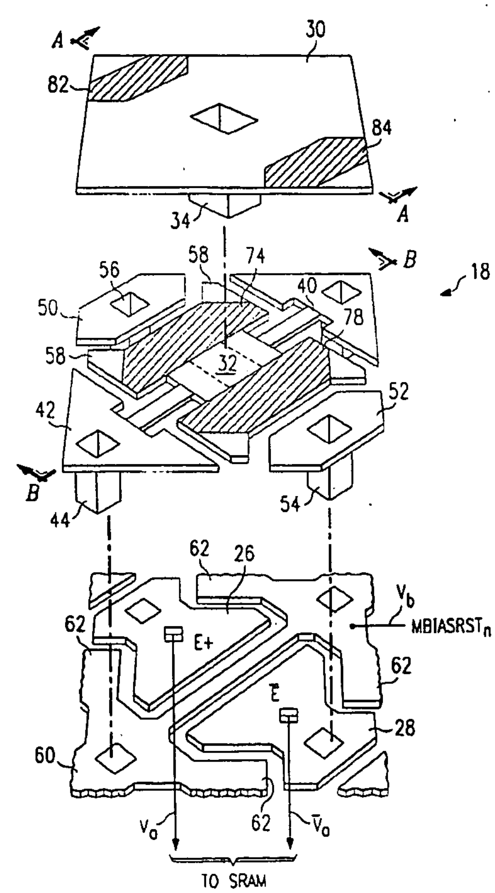
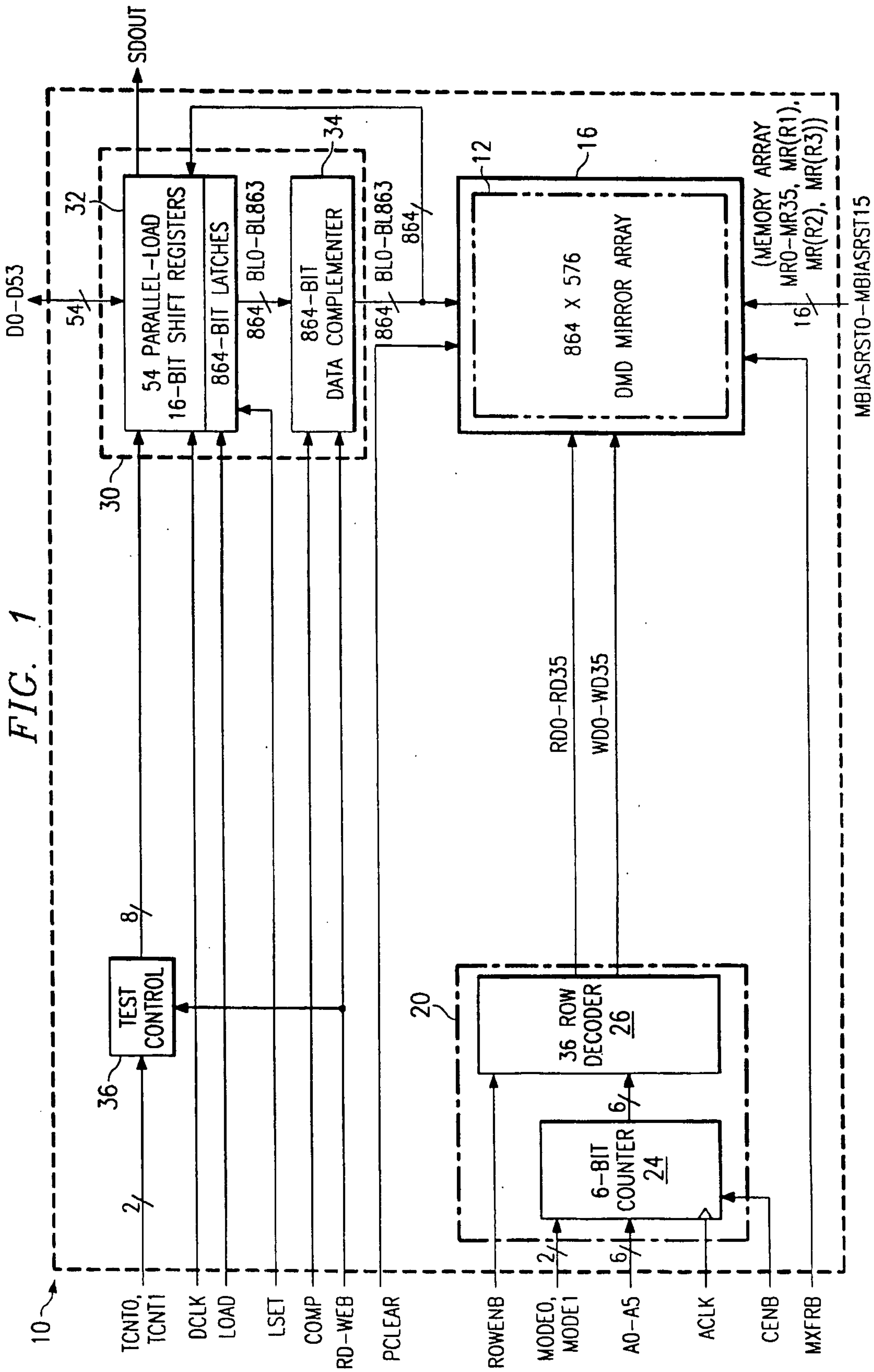
Primary Examiner—Loha Ben
Attorney, Agent, or Firm—Robert C. Klinger; James C. Kesterson; Richard L. Donaldson

[57] ABSTRACT

A spatial light modulator (10) of the DMD type having increased performance parameters. A pixel mirror (30) is supported by a yoke (32), whereby electrostatic attraction forces (70, 76, 80, 82) are generated between several structures. First, between the elevated mirror (30) and an elevated address electrode (50, 52). Second, between the yoke (32) and an underlying address electrode (26, 28). The pixel (30) achieves high address torque, high latching torques, high reset forces, and greater address margins over previous generation devices. The proximity of the yoke (32) over the substrate address electrodes (26, 28) realizes large attraction forces whereby the pixel is less susceptible to address upset, requires lower reset voltages and provides higher switching speeds.

18 Claims, 8 Drawing Sheets

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D0-D53
54
32
54 PARALLEL-LOAD 16-BIT SHIFT REGISTERS
864-BIT LATCHES
BL0-BL863
864
34
864-BIT DATA COMPLEMENTER
BL0-BL863
864
864
864
12
16
864 X 576
DMD MIRROR ARRAY
(MEMORY ARRAY MR0-MR35, MR(R1), MR(R2), MR(R3))
16
MBIASRST0-MBIASRST15
30
RD0-RD35
WD0-WD35
8
TEST CONTROL
36
2
20
36 ROW DECODER 26
6
6-BIT COUNTER 24
2
6
10
TCNT0, TCNT1
DCLK
LOAD
LSET
COMP
RD-WEB
PCLEAR
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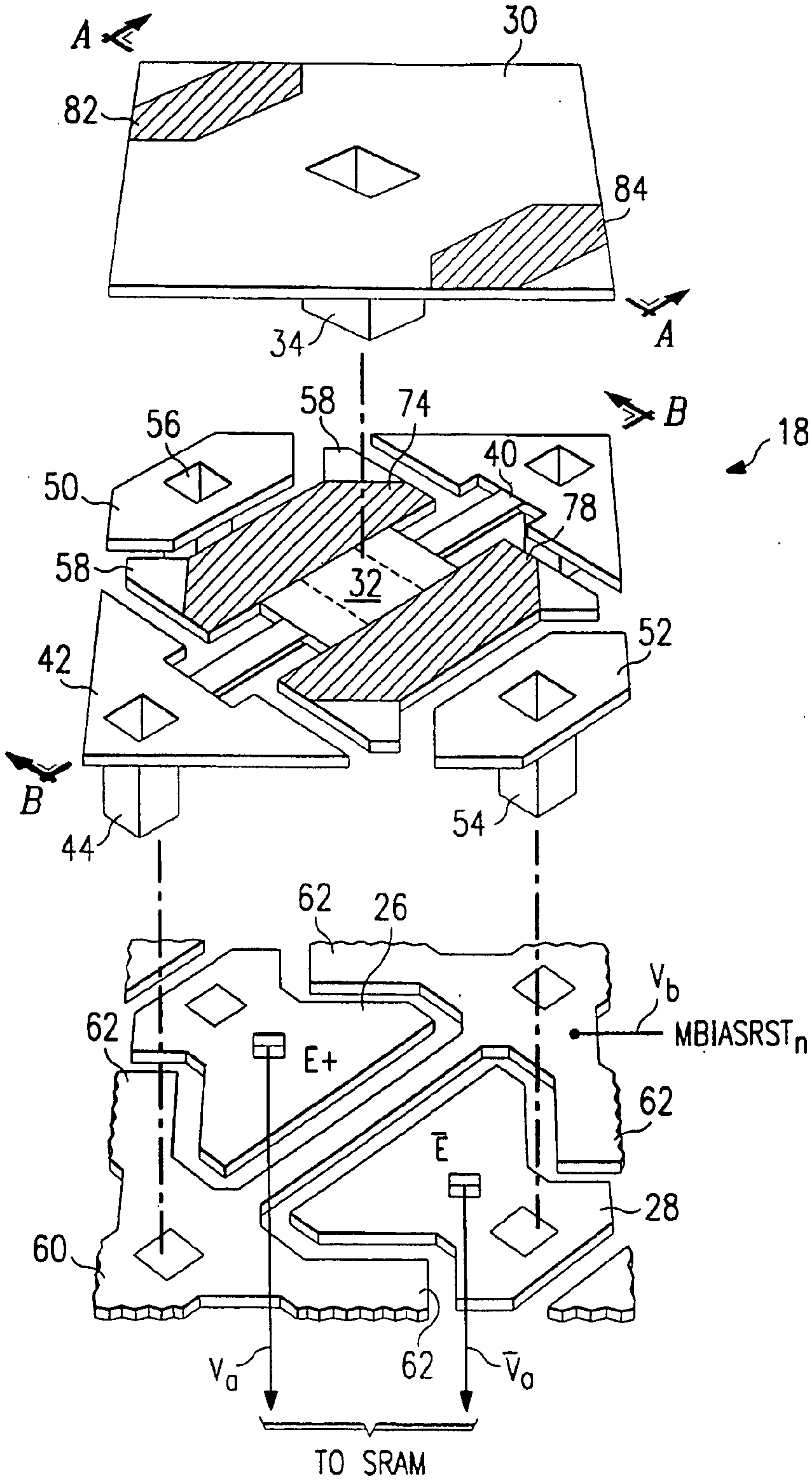
MODE0, MODE1
A0-A5
ACLK
CENB
MXFRB

FIG. 1


A
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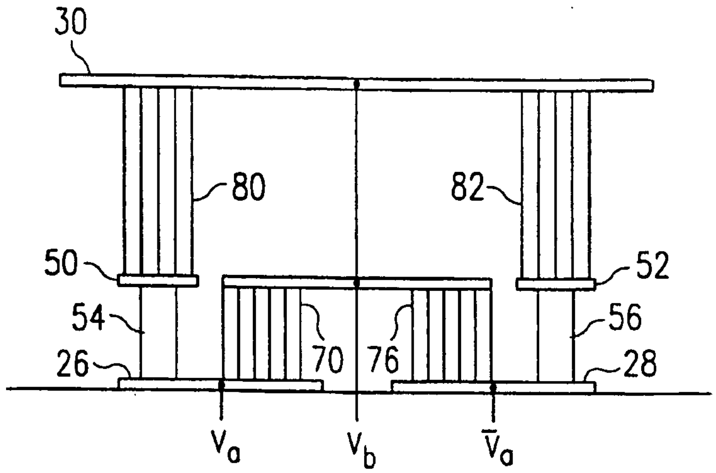
84
A
34
58
74
B
18
56
40
50
78
58
32
42
52
B
54
44
62
26
V_b
62
E+
$MBIASRST_n$
62
$\bar{E}$
28
60
V_a
62
$\bar{V}_a$
TO SRAM

FIG. 2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70
76
28
V_a
V_b
$\bar{V}_a$

FIG. 3

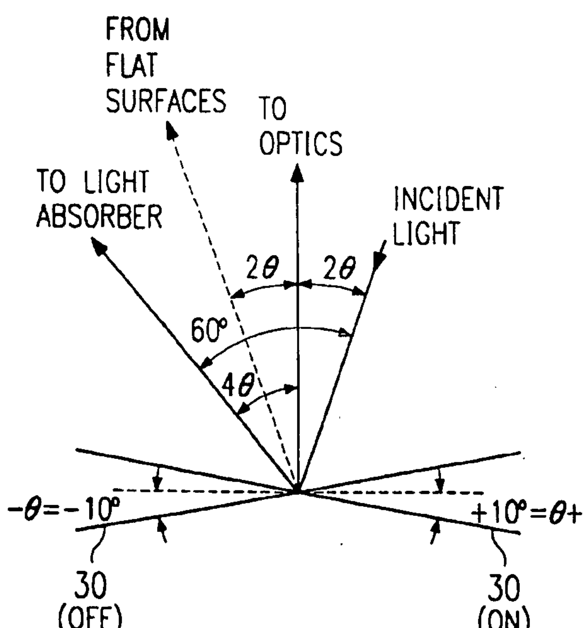

FROM FLAT SURFACES
TO OPTICS
TO LIGHT ABSORBER
INCIDENT LIGHT
2θ
2θ
60°
4θ
-θ=-10°
+10°=θ+
30 (OFF)
30 (ON)

FIG. 5

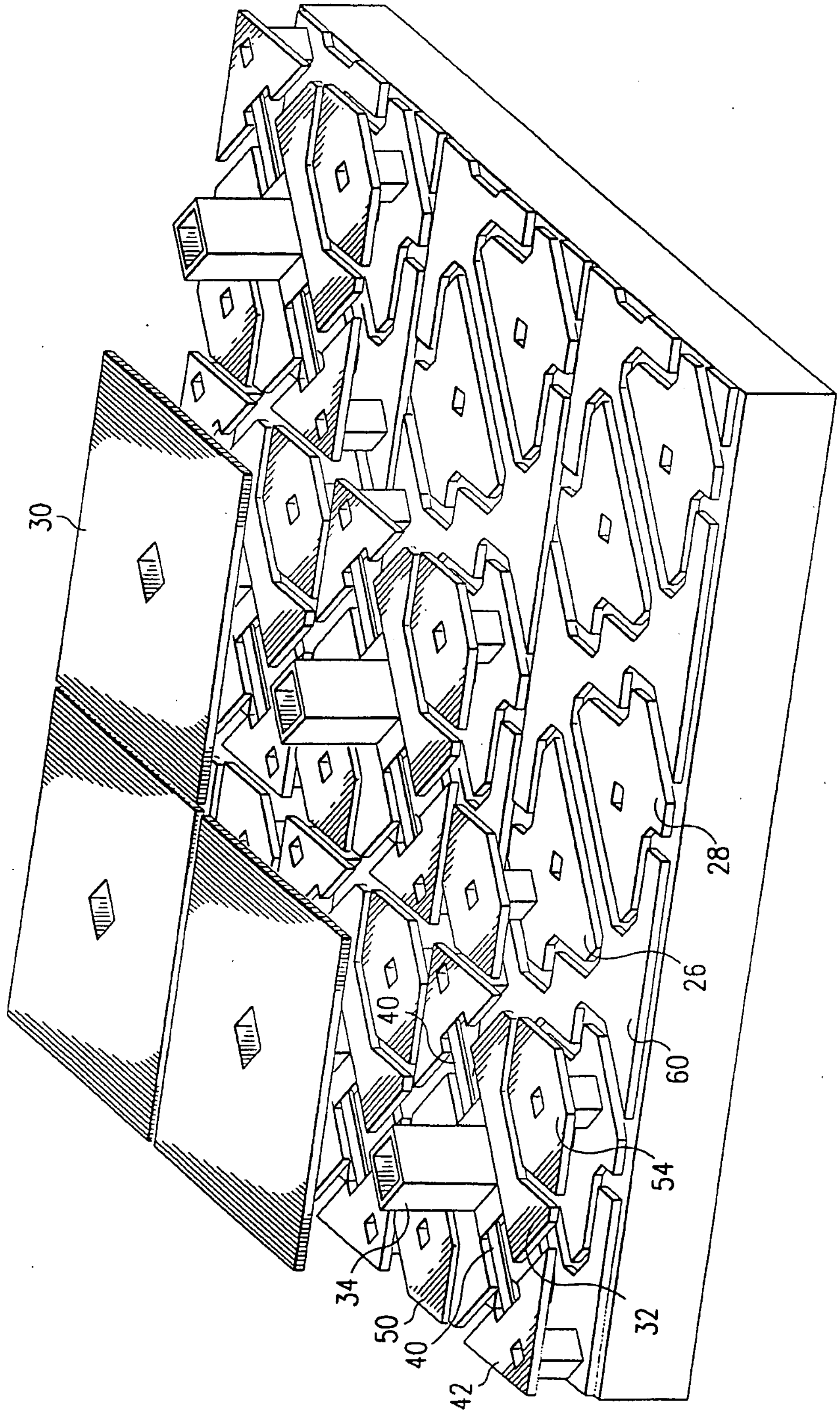


FIG. 4

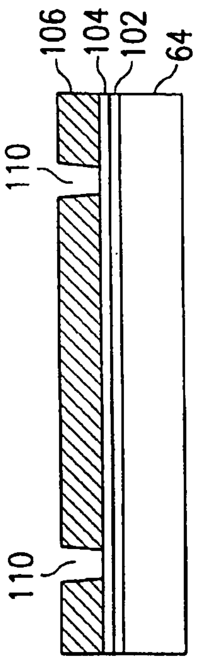


FIG. 8

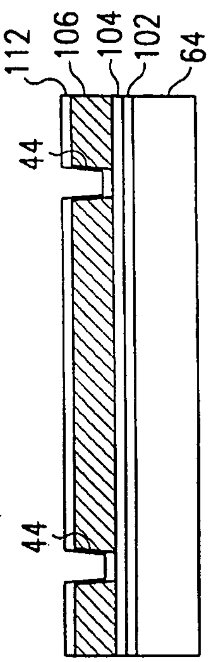


FIG. 9

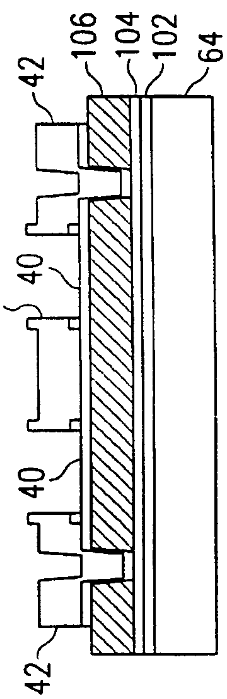


FIG. 10

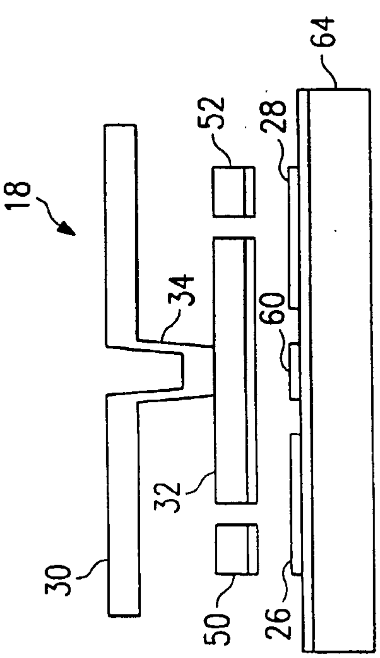


FIG. 6

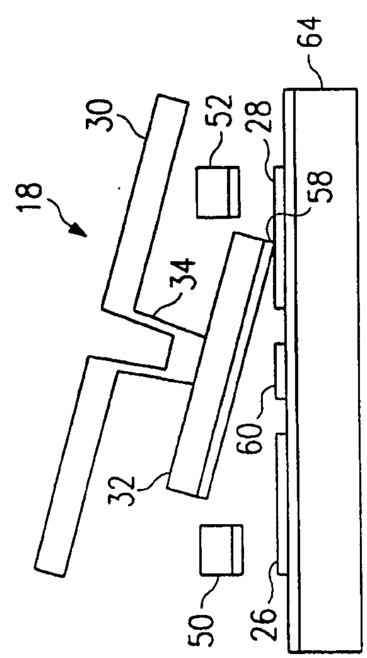


FIG. 7

07/17/2002, EAST Version: 1.03.0002

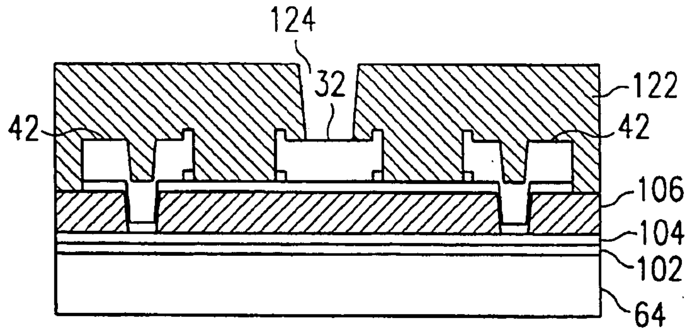


FIG. 11

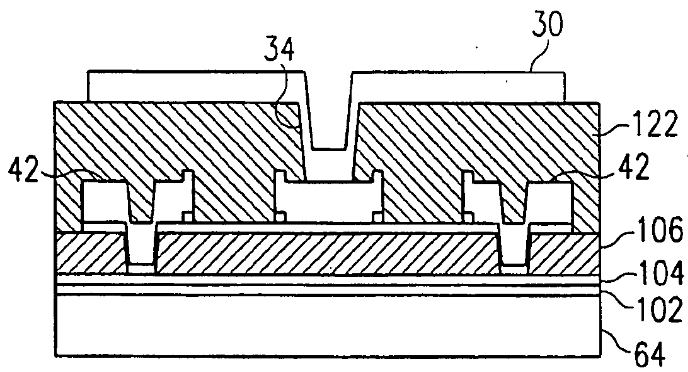


FIG. 12

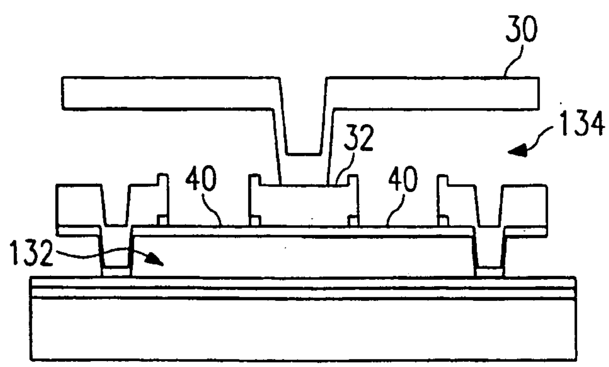
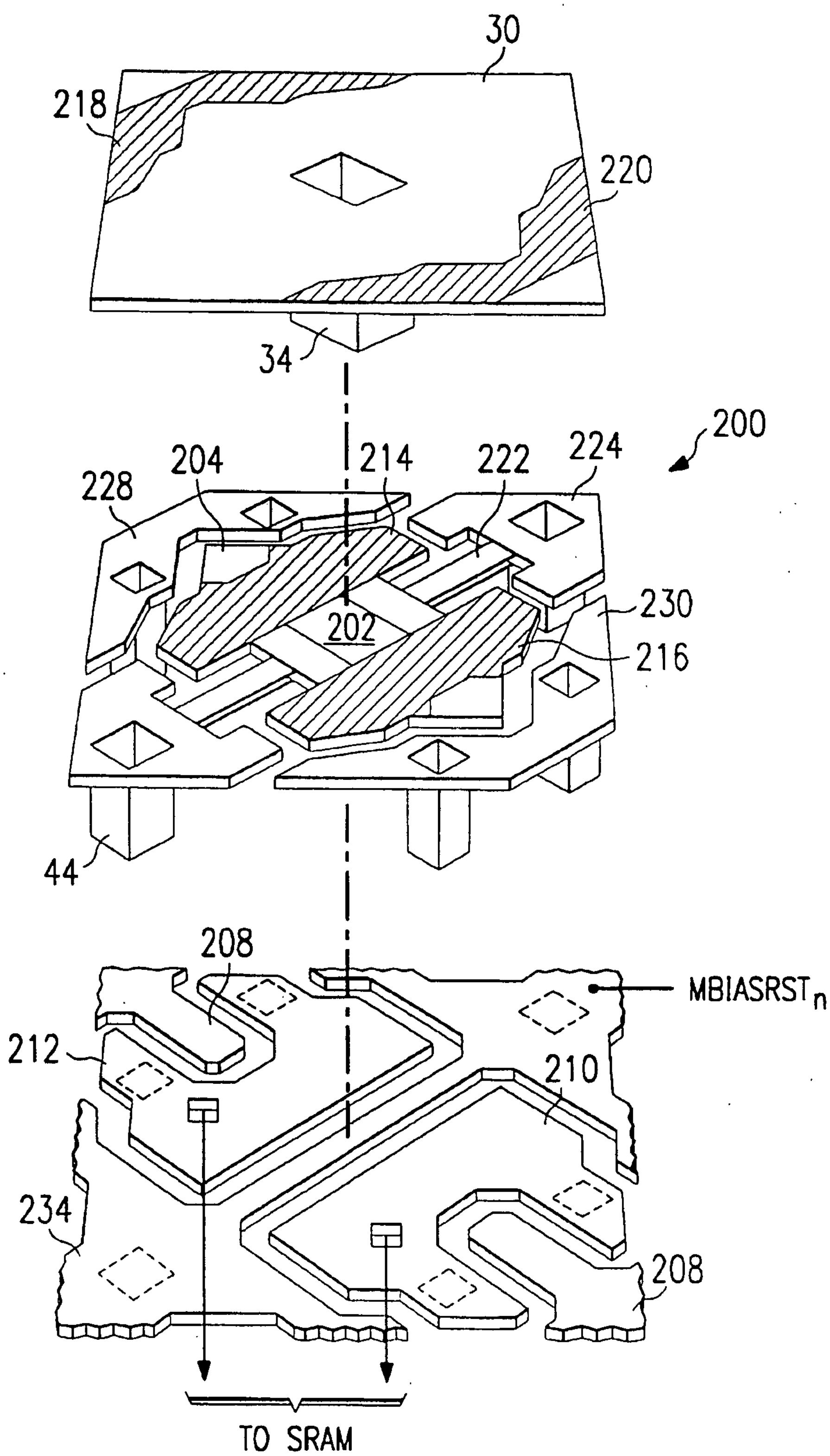
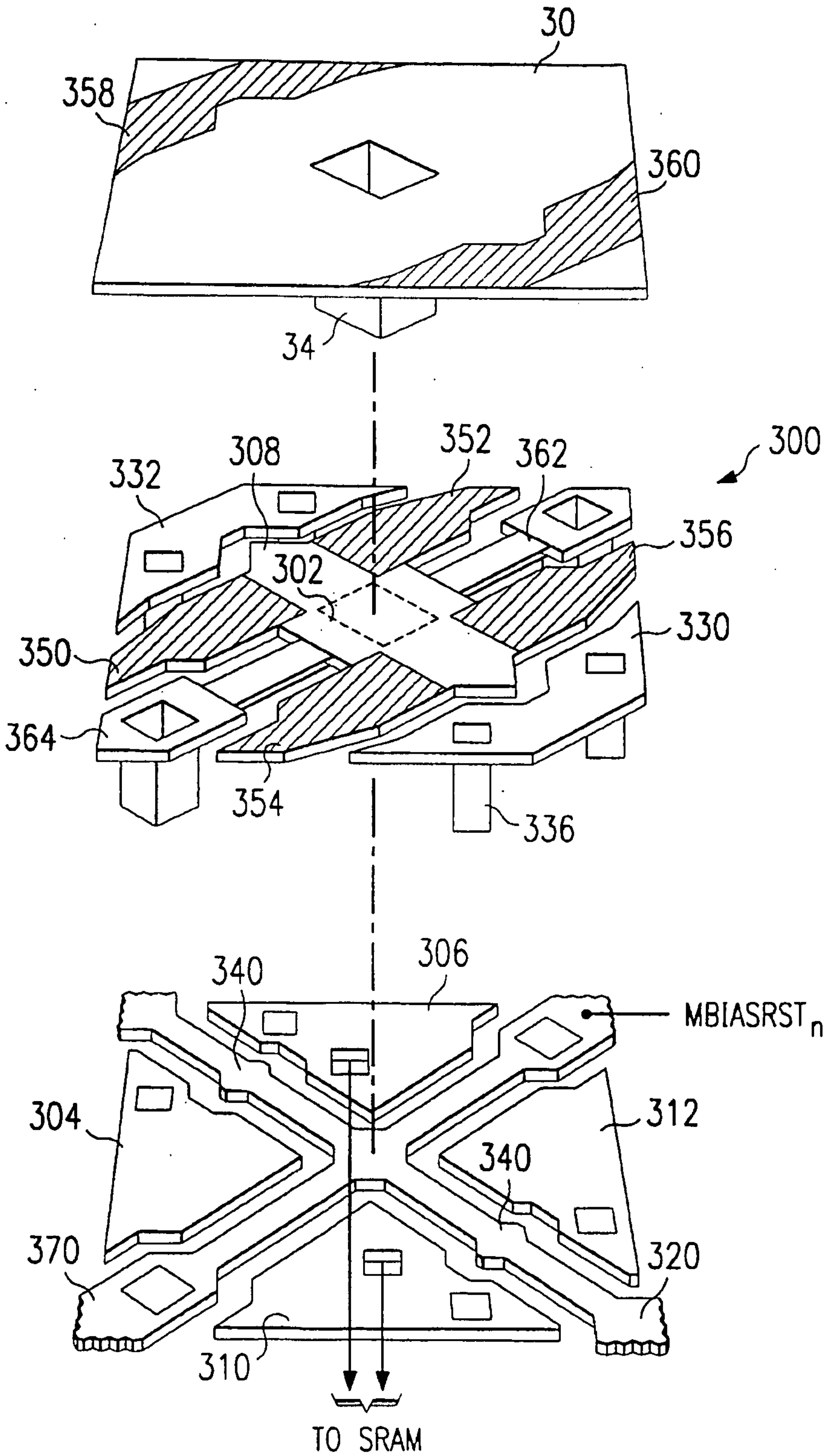


FIG. 13



30
218
220
34
200
228
204
214
222
224
230
202
216
44
208
MBIASRST$_n$
212
210
234
208
TO SRAM

FIG. 14


30
358
360
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300
332
308
352
362
356
302
330
350
364
354
336
306
340
MBIASRST$_n$
304
312
340
370
320
310
TO SRAM

FIG. 15

ACTIVE YOKE HIDDEN HINGE DIGITAL MICROMIRROR DEVICE

CROSS REFERENCE TO RELATED APPLICATION

Cross reference is made to the following commonly assigned co-pending patent applications the teachings of which are incorporated herein by reference:

SER. NO.	TITLE	FILING DATE
08/171,303	Improved Multi-Level Digital Micromirror Device	12-21-93
08/239,497	PFPE Coatings for Micro-Mechanical Devices	05-09-94
08/373,692	Monolithic Programmable Format Pixel Array	01-17-95
08/382,566	Spatial Light Modulator with Buried Passive Charge Storage Cell Array	02-02-95
08/300,356	Pixel Control Circuitry for Spatial Light Modulator	09-02-94
TI18138 (Attorney's Docket)	Spatial Light Modulator with Superstructure Light Shield	03-31-95
08/389,673	Single Bit Line Split Reset Memory Cell for Digital MicroMirror Device Display Array	02-16-95
08/396,024	Method for Creating a Digital Micromirror Device Using an Aluminum Hard Mask	02-27-95

TECHNICAL FIELD OF THE INVENTION

The present invention is generally related to spatial light modulators for modulating incident light to form an optical light image, and more particularly, to a digital micromirror device (DMD) having an array of bistable micromirrors fabricated over addressing circuitry.

BACKGROUND OF THE INVENTION

Spatial Light Modulators (SLMs) have found numerous applications in the areas of optical information processing, projection displays, video and graphics monitors, televisions, and electrophotographic printing. SLMs are devices that modulate incident light in a spatial pattern to form a light image corresponding to an electrical or optical input. The incident light may be modulated in its phase, intensity, polarization, or direction. The light modulation may be achieved by a variety of materials exhibiting various electro-optic or magneto-optic effects, and by materials that modulate light by surface deformation.

An SLM is typically comprised of an area or linear array of addressable picture elements (pixels). Source pixel data is first formatted by an associated control circuit, usually external to the SLM, and then loaded into the pixel array one frame at a time. This pixel data may be written to the pixel array using a variety of algorithms, i.e. sequentially top-to-bottom one pixel line at a time, interleaving by sequentially addressing top-to-bottom ever other pixel line, such as the odd rows of pixels, and then returning to address the even pixel lines, etc. In cathode ray tubes (CRTs), this data writing technique is know as rasterizing, whereby a high powered electron gun scans across the pixel elements of a phosphor screen left to fight, one line at a time. This pixel address data writing scheme is equally applicable to liquid crystal displays (LCDs) as well.

A recent innovation of Texas Instruments Incorporated of Dallas Tex., is the digital micromirror device or the deformable mirror device (collectively DMD). The DMD is an electro/mechanical/optical SLM suitable for use in displays, projectors and hard copy printers. The DMD is a monolithic single-chip integrated circuit SLM, comprised of a high density array of 16 micron square movable micromirrors on 17 micron centers. These mirrors are fabricated over address circuitry including an array of SRAM cells and address electrodes. Each mirror forms one pixel of the DMD array and is bistable, that is to say, stable in one of two positions, wherein a source of light directed upon the mirror array will be reflected in one of two directions. In one stable "on" mirror position, incident light to that mirror will be reflected to a projector lens and focused on a display screen or a photosensitive element of a printer. In the other "off" mirror position, light directed on the mirror will be deflected to a light absorber. Each mirror of the array is individually controlled to either direct incident light into the projector lens, or to the light absorber. The projector lens ultimately focuses and magnifies the modulated light from the pixel mirrors onto a display screen and produce an image in the case of a display. If each pixel mirror of the DMD array is in the "on" position, the displayed image will be an array of bright pixels.

For a more detailed discussion of the DMD device and uses, cross reference is made to U.S. Pat. No. 5,061,049 to Hornbeck, entitled "Spatial Light Modulator and Method"; U.S. Pat. No. 5,079,544 to DeMond, et al, entitled "Standard Independent Digitized Video System"; and U.S. Pat. No. 5,105,369 to Nelson, entitled "Printing System Exposure Module Alignment Method and Apparatus of Manufacture", each patent being assigned to the same assignee of the present invention and the teachings of each are incorporated herein by reference. Gray scale of the pixels forming the image is achieved by pulse-width modulation techniques of the mirrors, such as that described in U.S. Pat. No. 5,278,652, entitled "DMD Architecture and Timing for Use in a Pulse-Width Modulated Display System", assigned to the same assignee of the present invention, and the teachings of which are incorporated herein by reference.

The DMD is revolutionary in that it is truly a digital display device and an integrated circuit solution. The evolution and variations of the DMD can be appreciated through a reading of several commonly assigned patents. The "first generation" of DMD spatial light modulators implemented a deflectable beam wherein the mirror and the beam were one in the same. That is, an electrostatic force was created between the mirror and the underlying address electrode to induce deflection thereof. The deflection of these mirrors can be variable and operate in the analog mode, and may comprise a leaf-spring or cantilevered beam, as disclosed in commonly assigned U.S. Pat. No. 4,662,746 to Hornbeck, entitled "Spatial Light Modulator and Method", U.S. Pat. No. 4,710,732 to Hornbeck, entitled "Spatial Light Modulator and Method", U.S. Pat. No. 4,956,619 to Hornbeck, entitled "Spatial Light Modulator", and U.S. Pat. No. 5,172,262 to Hornbeck, entitled "Spatial Light Modulator and Method", the teachings of each incorporated herein by reference.

This first generation DMD can also be embodied as a digital or bistable device. The beam (mirror) can include a mirror supported by a torsion hinge and axially rotated one of two directions 10 degrees, until the mirror tip lands upon a landing pad. Such an embodiment is disclosed in commonly assigned U.S. Pat. No. 5,061,049 to Hornbeck entitled "Spatial Light Modulator and Method". To limit the

Van der Waals forces between the mirror tips and the landing pads, the landing pads may be passivated by an oriented monolayer formed upon the landing pad. This monolayer decreases the Van der Waals forces and prevents sticking of the mirror to the electrode. This technique is disclosed in commonly assigned U.S. Pat. No. 5,331,454 to Hornbeck, entitled "Low Reset Voltage Process for DMD", the teachings included herein by reference.

A "second generation" of the DMD is embodied in commonly assigned U.S. Pat. No. 5,083,857 entitled "Multi-Level Deformable Mirror Device", as well as in copending patent application Ser. No. 08/171,303 entitled "Improved Multi-Level Digital Micromirror Device, filed Dec. 21, 1993. In this second generation device, the mirror is elevated above a yoke, this yoke being suspended over the addressing circuitry by a pair of torsion hinges. As depicted in FIG. 3c of this application, an electrostatic force is generated between the elevated mirror and an elevated electrode. When rotated, it is the yoke that comes into contact with a landing electrode, whereby the mirror tips never come into contact with any structure. The shorter moment arm of the yoke, being about 50% of the mirror, allows energy to be more efficiently coupled into the mirror by reset pulses due to the fact that the mirror tip is free to move. Applying resonant reset pulses to the mirror to help free the pivoting structure from the landing electrode is disclosed in commonly assigned U.S. Pat. No. 5,096,279, entitled "Spatial Light Modulator and Method, and U.S. Pat. No. 5,233,456 entitled "Resonant Mirror and Method of Manufacture". However, some of the address torque generated between the mirror and the elevated address electrode is sacrificed compared to the first generation devices because the yoke slightly diminishes the surface area of the address electrode.

It is desired to provide an improved DMD having a more efficient reset action, and to develop a device with more address torque, latching torque, and address holding torque. The improved device would preferably be fabricated using the baseline fabrication processes.

SUMMARY OF THE INVENTION

The present invention achieves technical advantages as a DMD spatial light modulator by laterally extending the yoke in a direction parallel to the hinges, so that the yoke overlaps a substantial portion of a first pair of address electrodes. A second pair of elevated address electrodes are provided lateral of the yoke and beneath an elevated mirror supported by the yoke. Address torque is achieved between the first pair of address electrodes and the yoke, and between the elevated second pair of address electrodes and the elevated mirror. The yoke is spaced closer to the underlying address electrodes than the mirror is positioned relative to the elevated address electrodes. Since force per unit area between the opposing members is proportional to one over the square of the distances, the force per unit area between the yoke and the underlying first pair of address electrodes is up to 4× greater than the force per unit area between the mirror and the elevated second pair of address electrodes. The present invention has superior address torque, latching torque, address holding torque and reset force compared to earlier generations, with no change in process flow.

The present invention comprises a spatial light modulator including a substrate. Addressing circuitry comprising a first portion is provided proximate the substrate, and also comprises a second portion elevated above the substrate. A yoke is supported over the first portion of the addressing circuitry.

At least one hinge is connected to the yoke and supports the yoke, with the hinge permitting deflection of the yoke over the addressing circuitry first portion. A pixel is elevated above and supported by the yoke, this pixel being positioned over the elevated addressing circuitry second portion. The first and second portions of the addressing circuitry are electrically connected to one another, whereby a potential provided to the first and second portions creates an electrostatic force in two places. First, an electrostatic force is generated between the yoke and the addressing circuitry first portion, and secondly, between the elevated pixel and the elevated second portion.

The distance between the yoke and the first portion is approximately half the distance defined between the pixel and the elevated second portion. The opposing surface areas of the yoke and address circuitry first portion realize an addressing torque that is approximately 4× greater than the addressing torque generated between the elevated pixel and the elevated second electrode. The net address torque is additive, and is substantially greater than the address torque generated by earlier generation DMD devices.

The yoke preferably has a butterfly like shape, having a pair of yoke tips on each side of a yoke axis. When rotated, one pair of yoke tips lands upon a landing pad, whereby the supported and elevated pixel mirror remains free of any structure. Thus, reset pulses can be provided to the mirror, preferably at a frequency being the resonant frequency of the mirror to achieve a good reset action. The yoke is preferably in substantially the same plane as the hinges and may be fabricated using a single etch process so that the hinges are formed for precision alignment and balancing.

The spatial light modulator further comprises control circuitry connected to the addressing circuitry. This control circuitry provides address data to both the first and second portions of the addressing circuitry to cause deflection of the pixel. Preferably, a first portion of the addressing circuitry, comprising a pad, is provided each side of the pixel axis of rotation, with a separate second portion of the addressing circuitry being provided under the pixel each side of this yoke axis. The control circuitry provides address data to one of either of these sets of addressing portions to cause deflection of the yoke and mirror toward the addressing portions to cause deflection of the yoke and mirror toward the addressed first and second portions. Preferably, the pixel is a mirror, having a rectangular shape with geometrically oriented edges at 45° with respect to the hinge to minimize diffraction terms generated along the edges of the pixel that are perceived by darkfield optics.

The DMD device having a yoke suspended over a pair of address electrodes, and supporting an elevated mirror extending over a second pair of address electrodes, achieves a significant increase in the attractive area between address electrodes and the pivotable structure, namely, the yoke and the mirror. The underlying address electrodes on the substrate, comprised of metal **3**, are carefully designed to maximize the attractive area while permitting the yoke tips to land on landing electrodes having the same potential as the mirror and yoke. The elevated address electrodes for the mirror have been modified from the second generation device to accommodate the extended yoke of the present invention, while maintaining most of the torque that can be generated between the mirror and elevated electrodes. Any lost torque due to a reduced area of the elevated electrodes is more than compensated for by the yoke extensions overlying the address electrodes, these address electrodes being positioned half the distance from the yoke than the mirror is positioned to the elevated electrodes. The net

address torque that can be generated compared to the second generation device is almost a factor of two greater. The present invention also achieves a greater latching torque and address holding torque.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a spatial light modulator according to the preferred embodiment of the present invention, including row address and column data loading circuitry for controlling an array of pixels comprising micromirrors;

FIG. 2 is an exploded perspective view of one DMD pixel of the array shown in FIG. 1, including an elevated micromirror fabricated upon a deflectable yoke, the yoke in turn being supported by a pair of hinges, the hashed areas illustrating the region of electrostatic attraction between the elevated mirror and an elevated address electrode, and between the yoke and the underlying address electrode comprising metal 3 upon the substrate;

FIG. 3 is an illustration of the electrostatic attraction forces between the mirror and the elevated address electrode, and between the yoke and the underlying address electrode, the yoke and mirror being electrically connected to a bias/reset bus and having the same voltage bias;

FIG. 4 is a sectioned view of a 3×3 array of pixels from that array shown in FIG. 1, with some of the yokes, elevated address electrodes, and hinge support posts being removed to illustrate the metal 3 layer defining the substrate level address electrodes and the substrate level bias/reset patterns, and also illustrating some of the elevated mirrors being removed to depict the elevated yoke which overlaps portions of the underlying substrate level address electrodes;

FIG. 5 is an illustration of the two stable deflected states of the pixel mirror shown in FIG. 4 for deflecting incident light in one of two directions;

FIG. 6 is cross-sectional view of one pixel of the DMD array of FIG. 1 taken along the hinge axis to illustrate the elevated mirror address electrodes and the yoke supported over a pair of substrate address electrodes;

FIG. 7 is also a cross-sectional view such as that of FIG. 6, with the yoke and the mirror supported thereon together being rotated to one stable state, whereby the yoke tips land upon a pair of respective landing pads, while the elevated mirror remains proximate but spaced from the elevated mirror address electrodes;

FIG. 8–13 sequentially illustrate the various layers of semiconductor material which are processed to fabricate the pixel of FIG. 2 using conventional robust semiconductor processing techniques;

FIG. 14 is a exploded perspective view of an alternative preferred embodiment of the present invention whereby the yoke has only one landing tip defined each side of the torsion axis; and

FIG. 15 is an exploded perspective view of yet another alternative preferred embodiment of the present invention, whereby the yoke has a single landing tip each side of the torsion axis, and wherein the yoke is extended parallel to the torsion axis over the underlying substrate address electrode.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, a spatial light modulator comprising a digital micromirror device (DMD) is generally shown at 10. DMD 10 is a single-chip integrated circuit seen to include an 864×576 micromirror array 12. Array 12 is monolithically fabricated over a 864×36 memory cell array 16. Each memory cell in the 36 memory cells rows (MR0-MR35) forming memory cell array 16 is associated with and controlling a dedicated group of sixteen (16) pixels 18, shown in FIG. 2. Each memory cell comprises a primary 1-bit static random access memory (SRAM) cell, and a secondary 1-bit SRAM cell fed by the primary cell. There are 864 bit lines BL0-BL863 connected to one of each of the 864 columns of memory cells. Column pixel data is loaded into the addressed primary memory cell row MR_n via the associated bit lines BL0-BL863. The primary memory cell is addressed by enabling the associated row write or read enable line, identified as the WD_n or RD_n, respectively, whereby WP_n is connected to the enable input of each primary cell in the row MR_n. This pixel data is latched from the primary cell into the respective secondary cell by enabling the global control line MXFRB, the MXFRB line being connected to the enable input of all secondary cells of array 16. The secondary memory cell essentially operates as a shadow latch, whereby data can be loaded from the primary memory cell into the secondary memory cell, allowing the primary memory cell to then be subsequently reloaded with new pixel data without effecting the memory cell contents of the secondary memory cell. For additional discussion of this shadow latch technique, cross reference is made to commonly assigned co-pending patent application Ser. No. 08/389,673 entitled "Spatial Light Modulator Having Single Bit-Line Dual-Latch Memory Cells", filed Feb. 16, 1995, the teachings of which are incorporated herein by reference. For a more detailed discussion of the control circuitry, including the row address and column data loading circuitry, as well as the test control functions of DMD 10, cross reference is made to commonly assigned co-pending patent application Ser. No. 08/373,692, entitled "Monolithic Programmable Format Pixel Array" filed Jan. 17, 1995, the teaching of which are included herein by reference.

Referring now to FIG. 2, one pixel 18 of mirror array 12 is shown. The data of the secondary memory cell is provided to a pair of complementary address electrode lines, each line in turn being connected to one of two address electrodes 26 and 28 fabricated under and associated with each pixel 18 of array 12. Pixel 18 is seen to include a square mirror 30 supported upon and elevated above a yoke generally shown at 32 by a support post 34. Support post 34 extends downward from the center of the mirror, and is attached to the center of the yoke 32 along a torsion axis thereof, as shown, to balance the center of mass of mirror 30 upon yoke 32. Yoke 32 has a generally butterfly shape, that will be discussed in more detail shortly, and is axially supported along a central axis thereof by a pair of torsion hinges 40. The other end of each torsion hinge 40 is attached to and supported by a hinge support post cap 42 defined on top of a respective hinge support post 44. A pair of elevated rain or address electrodes 50 and 52 are supported by a respective address support post 54 and 56.

The address support post 54 and 56, and the hinge support posts 44 support the address electrodes 50 and 52, the torsion hinges 40, and the yoke 32 away from and above a bias/reset bus 60, and the pair of substrate level address electrode pads 26 and 28. When mirror 30 and yoke 32 are together rotated about the torsion axis of the yoke, defined by the hinges 40, a pair of yoke tips 58 on the side of the yoke 32 that is deflected land upon and engage the bias/reset bus 60 at the landing sites 62.

Referring now to FIG. 2 in conjunction with FIG. 3, a technical advantage of pixel 18 according to the preferred

embodiment of the present invention will be discussed in considerable detail. Rotation of mirror **30** and yoke **32** can be achieved in one of two directions, to achieve a bistable state and modulate incident light as shown in FIG. **5** and will be discussed shortly. An address voltage is provided to one of the two address electrodes pads **26** or **28**, and to one of the corresponding elevated mirror address electrode **50** or **52** via the associated electrode support post **54** and **56**. This address voltage may be 5 volts which is compatible with CMOS logic circuitry, but could also comprise of other levels if desired. At the same time, +15 volt bias voltage is provided to bias/reset bus **60**, and thus to yoke **32** via support post **44**, post caps **42** and hinges **40**, as well as to mirror **30** via support **34**. The present invention achieves technical advantages by providing an electrostatic force between opposing surfaces at two locations illustrated by the hatched areas in FIG. 2. These electrostatic attractive forces are also illustrated at **70**, **76**, **80** and **82** in FIG. **3**.

By way of example, if mirror **30** and yoke **32** are to be rotated counter address line V_a while +5 volts is provided on the complementary address line $\overline{V}_a$. Thereafter, a +15 volt potential is provided on the bias line V_b to the bias/reset bus **60** to provide a +15 volt potential on yoke **32** and mirror **30**. An electrostatic attraction force from the 20 volt differential is generated between address electrode **26** and the portion of yoke **32** above this substrate address electrode, this force being shown generally at **70**. The corresponding portion of yoke **32** that over hangs the addressed electrode **26** is shown by the hatched portion illustrated at **74**. Conversely, if the mirror was to be rotated in a clockwise direction, a 0 volt potential would be provided to the complement address electrode **28**, to generate an attractive force at **76**, with the corresponding portion of the yoke **32** over hanging address electrode **28** being shown by the hatched region at **78**.

While an electrostatic attraction force is being generated at **70** between one half of yoke **32** and the underlying address electrode **26**, an electrostatic attractive force is also being generated between the elevated address electrode **50** and mirror **30** as shown at **80** in FIG. **3**. This electrostatic attractive force is generated by the voltage potential created between the portion of mirror **30**, shown at **82**, defined above the elevated address electrode **50**. The portion of mirror **30** overhanging address electrode **52** is shown at **84**. Therefore, by addressing one address electrode **26** or **28**, which in turn provides an address voltage to the corresponding elevated address electrode **50** or **52**, electrostatic attraction force is generated at two places, shown at **70** and **80**, or at **76** or **82**. Selectively applying this 0 volt address potential to one of the two address electrodes **26** or **28** determines which way mirror **30** and yoke **32** will rotate once the +15 volt potential is applied to the bias bus **60**, and consequently to the yoke **32** and mirror **30**.

Referring to FIG. **3**, it can be seen that the elevated address electrodes **50** and **52** are generally co-planar with the yoke **32**, each being spaced above the address electrodes **26** and **28** a distance of about 1 micron. The separation of mirror **30** above the elevated address electrodes **50** and **52** is approximately double this distance, or about 2 microns. Since the attractive force between opposing surfaces varies directly as a function of one over the square of the distance between the opposing surfaces, the electrostatic attractive force generated between yoke **32** and the address electrodes **26** and **28** per unit area is four times as great as the attractive force generated between mirror **30** and the corresponding elevated address electrode **50** and **52**. The forces generated each side of the torsion axis are additive, and together cause mirror **30** and yoke **32** to be rotated in the direction toward the address electrodes.

In an alternative embodiment, elevated electrodes **50** and **52** and their corresponding support posts can be eliminated. In this embodiment, the height of mirror **30** above yoke **32** is only about 1 micron to achieve a strong attractive force with the underlying distal lobe of electrodes **26** and **28**. When deflected, the mirror **30** will rotate toward, but will still not engage, the corresponding distal lobe of the address electrodes **26** and **28**. In this embodiment, the elevated structure including the posts **44**, yoke **32** and mirror **30** are all of equal potential and the risk of a short is avoided. Thus, limitation to one set of elevated electrodes is not to be inferred.

The address torque (T_a) is the torque produced by the address voltage alone with the yoke **32** and the mirror **30**. This address torque is significantly greater than the address torque generated by previous generation DMD devices for like address voltages and bias potentials. The present invention thus has an improved address margin, which is defined as the difference between the address voltage V_a and the potential that is required to ensure the mirror is rotated the proper direction when the bias voltage is applied.

The pixel of the present invention also has an increased latching torque (T_1), which is defined as a measure of the latching torque produced by the bias voltage in the presence of an address voltage tending to rotate (or upset) the mirror to the opposite state. Another dramatically improved performance parameter of the present invention is an increased address-holding torque (T_h), which is defined as a measure of the ability of the address voltage to hold the mirror in its landed state after reset during the time that the bias voltage is off. Another improved feature of the present invention is an increased reset force (F_r), which is defined as a measure of the tip reaction force produced by a combination of a single-pulse reset and the restoring force produced by the tip of the hinge.

All four of these performance parameters are substantially improved by the present invention over previous generation DMD devices due to the design of the yoke **32** generating an electrostatic attractive force with the underlying address electrodes, in combination with electrostatic attractive forces being generated between the elevated mirror and the elevated address electrodes. Due to the proximity of the rotatable yoke above the address electrodes, and a substantial opposing surface area thereof, all of the above mentioned performance parameters are significantly increased, and contribute to the increased electromechanical efficiency of the DMD device. In particular, for no change in hinge stiffness, a 1.8× higher address torque is achieved over previous generation devices. The latching torque is improved by 2.6× over that of previous DMD devices. The reset force generated is an 8.8× increase over that of previous generation DMD devices. With all the improved performance parameters, the process for fabricating the present invention, as will be described shortly, is nearly identical to that for the previous generation devices, thus providing a "something for nothing" benefit over previous generation devices.

The implications of the DMD device of the present invention includes greater address margin, as discussed, less susceptibility to address upset, lower reset voltage requirements, and higher switching speeds which is critical in the operation of the device as a spatial light modulator. With the present design, non-linear hinges can even be incorporated, with stiffer hinges if desired due to improve address margins and latching margins.

To reduce the possibility of stiction due to Van der Waals forces, the landing electrodes **60**, specifically at regions **62**

corresponding with the point of contact from tips **58** of yoke **32**, can be passivated. By passivating the landing electrodes, the tendency for the yoke **32** to adhere or stick can be decreased. Stiction is an inhibiting force that requires large reset voltages to be applied to reset the mirror to a flat state, or to switch the mirror to the opposing deflectable bistable state. Methods of passivating the landing electrodes are disclosed in commonly assigned U.S. Pat. No. 5,331,454 to Hornbeck, entitled "Low Reset Voltage Process for DMD", and in commonly assigned co-pending patent application Ser. No. 08/239,497 entitled "PFPE Coatings for Micro-Mechanical Devices", filed May 9, 1994, the teaching of each incorporated herein by reference. To achieve reset of the mirror, and induce deflection of the mirror to the other bistable state, the bias/reset line can be pulsed with a voltage at a frequency corresponding to the resonant frequency of the mirror, which is typically about 5 MHZ, such as disclosed in commonly assigned U.S. Pat. No. 5,096,279, entitled "Spatial Light Modulator and Method", the teachings of which are incorporated herein by reference.

Turning now to FIG. **4**, a sectioned perspective view of a 3×3 array portion of array **12** is shown to illustrate the fabrication of the metal **3** layer upon the silicon substrate, this metal **3** layer defining the address electrodes and the bias/reset buses upon the silicon substrate. Also illustrated is the elevated mirror address electrodes, the post caps, and the hinges supporting yoke **32** above the metal **3** layer. The mirror support post can be seen to be supported by the respective yoke along the torsion axis of the pixel.

Turning now to FIG. 5, an optical schematic diagram is shown whereby incident light is seen to be modulated and deflected in one of two directions, depending on whether the mirror is in the "on" or "off" state. When mirror 30 is in the on state, incident light is reflected to optics including a projector lens, and ultimately focused upon a display screen in the case of a front or rear screen projector, or focused upon a photosensitive surface in the case of a electrophotographic printer. When mirror **30** is in the off position, incident light is reflected to a light absorber and away from the darkfield optics. The 20° rotation between the bistable states of mirror **30** achieves a 40° swing of reflective incident light. Thus, the present invention achieves a high contrast ratio spatial light image, which is critical for use in darkfield optics systems for which the spatial light modulator of the present invention is intended.

Referring now to FIGS. **6** and **7**, a cross sectional view of pixel **18** taken alone line A—A in FIG. **2** is shown with the support posts not being shown. As shown in FIG. **6**, with yoke **32** and mirror **30** in the undeflected (flat) state, yoke **32** is generally coplanar with the elevated address electrodes 50 and 52, at a distance of about 1 micron above the metal 3 layer including address electrodes 26 and 28, and reset/bias bus 60. Mirror 30 is elevated above the pair of elevated address electrodes 50 and 52 about 2 microns, which is approximately double the distance separating the yoke from the substrate 64.

Referring to FIG. 7, when yoke 32 and mirror 30 are addressed and rotated in a clockwise direction, as shown, the pair of landing tips **58** of the addressed half of yoke **32** land upon portions **62** of reset/bias bus **60**. However, the elevated mirror **30**, while rotated therewith, remains spaced above and separated from the corresponding elevated address electrode **52**. As shown, the moment arm of yoke **32** is about half the moment arm of mirror **30** about the torsion axis. The shorter dimension of the landing yoke **32** compared to the mirror **30** reduces the torque necessary to reset a stuck mirror, while using too short a landing yoke can cause additional stress on the torsion hinges. A better understanding of these forces is described in commonly assigned co-pending patent application Ser. No. 08/171,303, entitled "Multi-Level Digital Micromirror Device", filed Dec. 21, 1993, the teachings of which are incorporated herein by reference. Since the yoke 32 lands upon a pair of opposing tips **58**, and is symmetrically designed, a large area of address electrode **26** and **28** can be defined under yoke **32**, as shown in FIG. 2. In addition, reduced stiction forces between the yoke and the landing electrode portions **62** has been observed, thus necessitating a lower reset voltage to be applied when changing or resetting the mirror state.

Referring now to FIGS. **8-13**, a detailed discussion of the semiconductor fabrication processes performed to fabricate one pixel **18** will be described. In each of the Figures, the section view is taken alone line B—B in FIG. 2 for purposes of illustration and clarity, although it is not to scale.

First, referring to FIG. **8**, a silicon substrate **64** is processed so as to form the underlying address circuitry including the array of memory cells **16**, the row address circuitry **20**, and the column data loading circuitry **30**. Thereafter, substrate **64** is covered with a protective oxide layer **102**. Next, a third layer of metalization, commonly referred to as M3, is sputter deposited onto the partially processed wafer and being shown at **104**. This third metalization layer is patterned and etched to define the address electrodes **26** and **28**, as well as the bias/reset bus **60** shown in FIG. 2 and FIG. 4. Next, a hinge spacer layer **106** is spin-deposited over the address circuitry and preferably comprises positive photoresist having a thickness of 1 micron. A pair of vias **110** are opened through the photoresist layer **106** to facilitate forming the hinge support post, then the layer of photoresist **106** is deep UV hardened at a high temperature to prevent flow and bubbling during subsequent processing steps.

Referring now to FIG. **9**, a thin hinge layer **112** of metalization is sputter deposited over the photoresist layer **106** and into vias **110**, as shown. Hinge layer **112** preferably has a thickness of about **500** Angstroms, and can be comprised of aluminum, aluminum alloys, titanium tungsten, and other conductive materials well suited for the present invention. The hinge support posts **44** are defined in this step as shown, and are electrically connected to bias/reset bus **60**. Also during this step, the pair of electrode support posts **54** and **56** are defined, although not shown, whereby the layer **112** is sputter deposited in a pair of corresponding vias formed in photoresist **106**, these vias having been formed during the previous step when vias **110** were opened. Thus, the electrode support post and the hinge support post are very similar. The thickness of the photoresist spacer layer **106** determines the hinge air gap, and thus, determines the mirror rotation angle due to the angular freedom of yoke **32** until it engages the landing electrodes.

Referring now to FIG. 10, a first mask of oxide is plasma-deposited, and patterned in the shape of the hinges 40. Then, a thick metal layer, typically about 3,000 Angstroms thick, of aluminum alloy is deposited. A second mask of oxide is plasma-deposited and then patterned in the shape of the yoke **32**, the elevated electrodes **54** and **56**, and the hinge support caps **42**. The thin hinge layer **112** and the thicker metal layer are then etched to define the address electrodes **50** and **52**, the hinge support caps **42**, and the hinges **40**, as shown. A single plasma etch is used to define these structures. The two oxide layers act as etch stops, and protect the metal layers beneath them. After completion of the plasma etch process, the oxide etch stops are removed from the thin metal hinges, the thicker metal support posts caps **42**, the electrodes **50** and **54**, and from the hinges **40**, as shown in FIG. **10**.

Referring now to FIG. 11, a thick mirror spacer layer 122 is spin-deposited over the hinges, electrodes and hinge support caps, and preferably comprises positive photoresist having a thickness of approximately 2 microns. A via 124 is opened in this photoresist spacer layer 122 to provide an opening above yoke 32, as shown, then the layer of photoresist 122 is deep UV hardened.

Referring to FIG. 12, a mirror metal layer, comprising of an aluminum alloy and having reflective properties, is then sputter-deposited to a thickness of about 4,000 Angstroms. This layer forms both the mirror support post 34 and the mirror 30. A masking oxide layer is then plasma-deposited onto the mirror layer, and patterned in the shape of the rectangular mirrors. The mirror metal layer is then plasma etched to form the mirror 30 and support post 34, as shown. The masking oxide layer is typically left in place while the wafer is subsequently processed and sawed to obtain dies. Referring to FIG. 13, the chips are placed in a plasma etching chamber, where the masking oxide layer and both spacer layers 106 and 122 are plasma etched away, leaving the hinge air gap under the hinges 40 and yoke 32, as well as a mirror air gap 134 beneath the elevated mirror 30.

Referring now to FIG. 14, a perspective exploded view of an alternative embodiment of the present invention is generally shown at 200. Pixel 200 is seen to be very similar to pixel 18 as discussed in regards to FIG. 1–13, wherein like numerals refer to like elements. However, pixel 200 has a yoke 202 which is slightly modified to have a single landing tip 204 each side of the torsion axis, as shown. When rotated, one tip 204 of yoke 202 will rotate until it engages and lands upon a corresponding landing electrode 208. The yoke 202 substantially overlaps each of a pair of address pads 210 and 212 formed from the metal 3 layer upon the substrate. The corresponding regions of opposing surfaces that create the electrostatic attraction forces are shown and hatched areas at 214, 216, 218, and 220, as shown. Hinges 222 support yoke 202 from hinge posts 224. Elevated address electrodes 228 and 230 are coplanar with yoke 202.

Referring now to FIG. 15, yet another alternative preferred embodiment of the present invention is shown at 300. Pixel 300 is very similar to the embodiment shown in FIG. 200, and to that pixel 18 shown in FIG. 1–13, where like numerals refer to like elements. Pixel 300, as shown, also has a single landing tip provided each side of the torsion axis, similar to the embodiment in FIG. 14. A yoke 302 is substantially extended parallel to the torsion axis and over the underlying address electrodes, where a pair of address electrodes 304 and 306 are provided beneath one side of yoke 302, and another pair of address electrodes 310 and 312 are provided on the other side of the bias/reset bus 320 which has an X-pattern, as shown. The two address electrodes 304 and 306 are electrically tied to one another, and the other pair of address electrodes 310 and 312 are electrically tied together. The pairs of address electrodes are electrically connected to the elevated mirror address electrodes 330 and 332 via a corresponding support post 336, as shown. The areas of electrostatic attraction are shown by the hatched areas of 350, 352, 354, 356, 358 and 360. Hinges 362 support yoke 302 from posts 364. In this embodiment, the bias/reset bus 320 has an X-shape, and bifurcates the pair of address electrodes, as shown. With an X-shape, the bias/reset bus can be easily and conveniently interconnected to adjacent pixels in the metal 3 layer upon the silicon substrate. This may yield a desirable layout for controlling multiple rows of pixels with a common bias/reset bus, and also facilitates the split-reset technique, such as disclosed in commonly assigned U.S. Patent application Ser. No. 08/300, 356, entitled "Pixel Control Circuitry for Spatial Light Modulator", filed Feb. 16, 1995, the teachings of which are incorporated herein by reference. The landing cites of the yoke tips are provided along the bias/reset bus, shown at 340.

In summary, a spatial light modulator of the DMD type is disclosed having electrostatic forces generated at two locations to induce deflection of the pixel mirror. First, an attractive force is generated between the yoke and an underlying substrate address electrode. Secondly, an electrostatic force is also generated between the elevated mirror and an elevated address electrode. These electrostatic forces are additive, and realize improved performance parameters over prior generation DMD devices. Since the yoke is separated above the substrate address electrodes by a distance equal to one-half the spacing between the mirror and the elevated address electrodes, an attractive force per unit area is 4× greater than the force generated between the mirror and the elevated electrodes is achieved. The design of the present invention achieves higher address torques, higher latching torques, higher reset forces, and greater address margins. The pixel is less susceptible to address upset, requires a lower reset voltage, and may eliminate the need for resonant reset and multiple reset pulses. Higher switching speeds are achieved, whereby non-linear and stiffer hinges can be implemented due to the improved performance parameters described. The pixel array can be fabricated with little deviation from the baseline process. Thus, the improved performance parameters achievable with the spatial light modulator of the present invention over previous generations is a "something for nothing" design over previous generations.

Though the invention has been described with respect to a specific preferred embodiment, many variations and modifications will become apparent to those skilled in the art upon reading the present application. It is therefore the intention that the appended claims be interpreted as broadly as possible in view of the prior art to include all such variations and modifications.

I claim:

1. A spatial light modulator, comprising:

a) a substrate;

b) addressing circuitry comprising a first portion provided proximate said substrate and a second portion elevated above said substrate;

c) a yoke supported over said addressing circuitry first portion;

d) at least one hinge connected to said yoke and supporting said yoke, said hinge permitting deflection of said yoke; and

e) a pixel elevated above and supported by said yoke, said pixel positioned over said elevated addressing circuitry second portion.

2. The spatial light modulator as specified in claim 1 comprising a pair of said hinges axially supporting said yoke along a yoke axis, wherein said addressing circuitry first portion is provided each side of said yoke axis.

3. The spatial light modulator as specified in claim 2 wherein said yoke has a pair of yoke tips on each side of said yoke axis.

4. The spatial light modulator as specified in claim 3 wherein said yoke has a butterfly shape.

5. The spatial light modulator as specified in claim 2 wherein a first pair of opposing surface areas are defined between said yoke and said addressing circuitry first portion, and a second pair of opposing surface areas are defined

between said pixel and said addressing circuitry second portion, said second pair of opposing surface areas being laterally defined a greater distance from said yoke axis than is said first pair of opposing surface areas from said yoke axis.

6. The spatial light modulator as specified in claim 2 further comprising control circuitry coupled to said addressing circuitry, said control circuitry providing address data to one of said addressing circuitry first portions to cause deflection of said yoke toward said addressed first portion.

7. The spatial light modulator as specified in claim 1 wherein said yoke has a width less than the width of said pixel and said pixel overlaps said yoke.

8. The spatial light modulator as specified in claim 1 wherein a first spacing is defined between said yoke and said addressing circuitry first portion, and a second spacing is defined between said pixel and said addressing circuitry second portion, wherein said first spacing is smaller than said second spacing.

9. The spatial light modulator as specified in claim 1 wherein said yoke is in substantially the same plane as said addressing circuitry second portion.

10. The spatial light modulator as specified in claim 1 further comprising a bias/reset bus constructed on said substrate and electrically connected to said pixel.

11. The spatial light modulator as specified in claim 1 wherein said hinge is in substantially the same plane as said yoke.

12. The spatial light modulator as specified in claim 1 further comprising control circuitry coupled to said addressing circuitry, said control circuitry providing address data to said addressing circuitry first portion and said second portion to cause deflection of said pixel.

13. The spatial light modulator as specified in claim 1 further comprising a support post connected to and supporting said hinge.

14. The spatial light modulator as specified in claim 1 wherein said addressing circuitry first portion and said second portion are electronically connected to one another.

15. The spatial light modulator as specified in claim 1 wherein said pixel is a mirror.

16. The spatial light modulator as specified in claim 15 wherein said mirror has a rectangular shape.

17. The spatial light modulator as specified in claim 16 wherein said mirror has edges geometrically oriented at 45° with respect to said hinge.

18. A spatial light modulator, comprising:

a) a substrate;

b) addressing circuitry comprising a first portion provided proximate said substrate and a second portion residing above a plane defined by said first portion;

c) a yoke supported over said addressing circuitry first portion;

d) at least one hinge connected to said yoke and supporting said yoke, said hinge permitting deflection of said yoke; and

e) a pixel elevated above and supported by said yoke, said pixel positioned over said elevated addressing circuitry second portion.

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